The Next Generation of Crystal Detectors

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Why Crystal Calorimeter in HEP?

- Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential.
- Performance of homogeneous crystal calorimeter in e/γ measurements is well understood:
  - The best possible energy resolution;
  - Good position resolution;
  - Good e/ γ identification and reconstruction efficiency.
- Challenges at future HEP Experiments:
  - Radiation damage at the energy frontier (HL-LHC);
  - Ultra-fast rate at the intensity frontier;
  - Good jet mass resolution at the energy frontier (ILC/CLIC).

Existing Crystal Calorimeters in HEP

Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS[a]+Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5

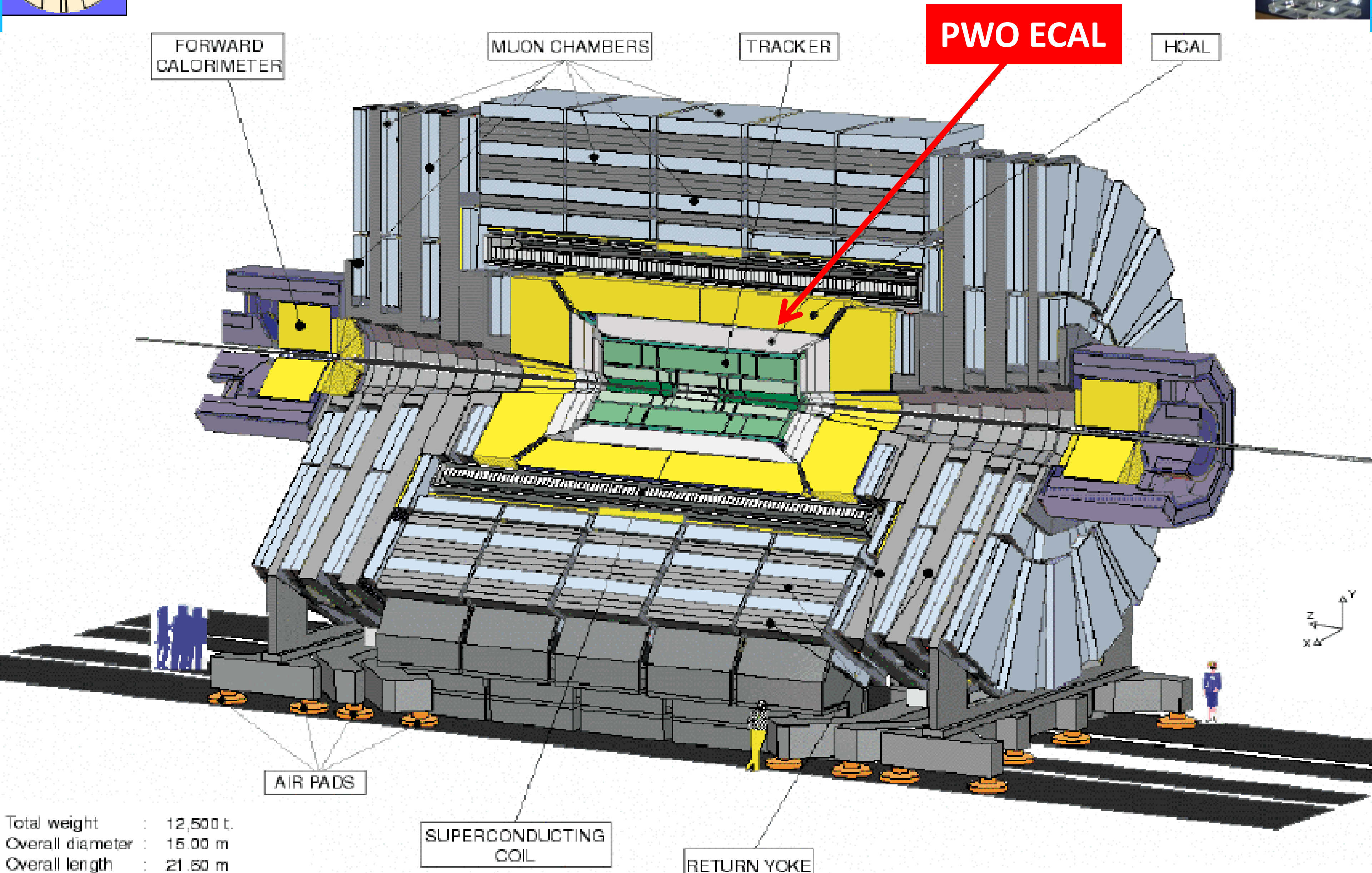
Future crystal calorimeters in HEP:

LSO/LYSO for HERD, (Mu2e, Super B) and HL-LHC (Sampling)

BaF_2 for fast calorimeter for Mu2e and project X

PbF_2, PbFCl, BSO for Homogeneous HCAL

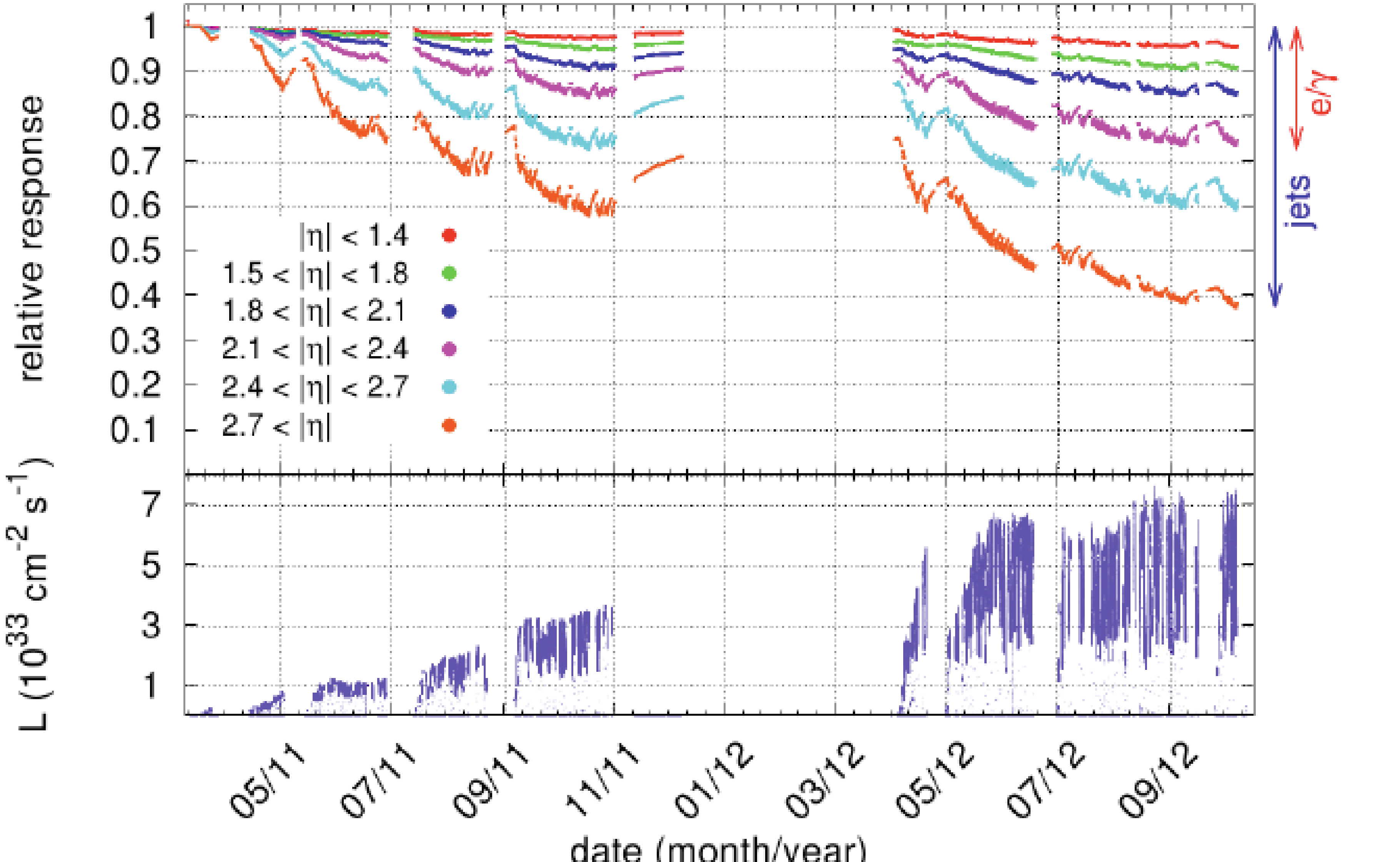
CMS Experiment at LHC



Total weight	:	12,500 t.
Overall diameter	:	15.00 m
Overall length	:	21.60 m
Magnetic field	:	4 Tesla

CMS PWO Monitoring Response

The observed degradation is well understood



Dose Rate Dependent Damage in LO

IEEE Trans. Nucl. Sci., Vol. 44 (1997) 458-476

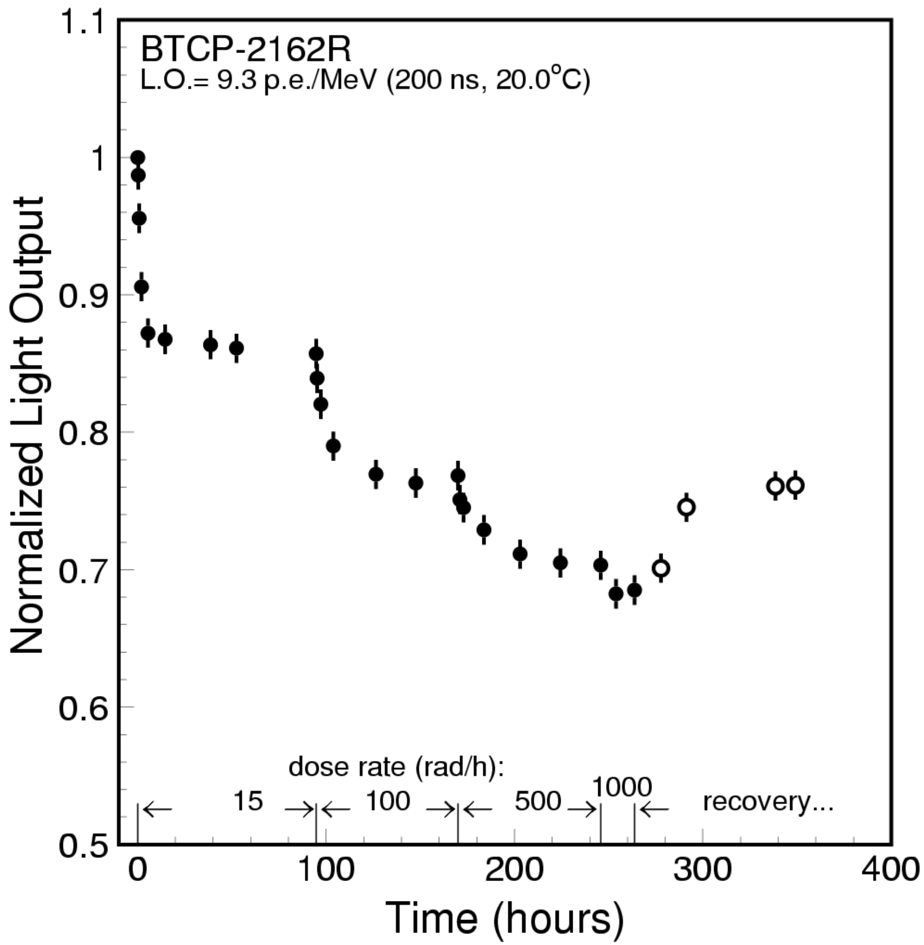
The LO reached equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

$$dD = \sum_{i=1}^{n} \{-a_i D_i dt + (D_i^{all} - D_i)\, b_i R dt\}$$

$$D = \sum_{i=1}^{n} \{\frac{b_i R D_i^{all}}{a_i + b_i R}\, [1 - e^{-(a_i + b_i R)t}] + D_i^0 e^{-(a_i + b_i R)t}\}$$

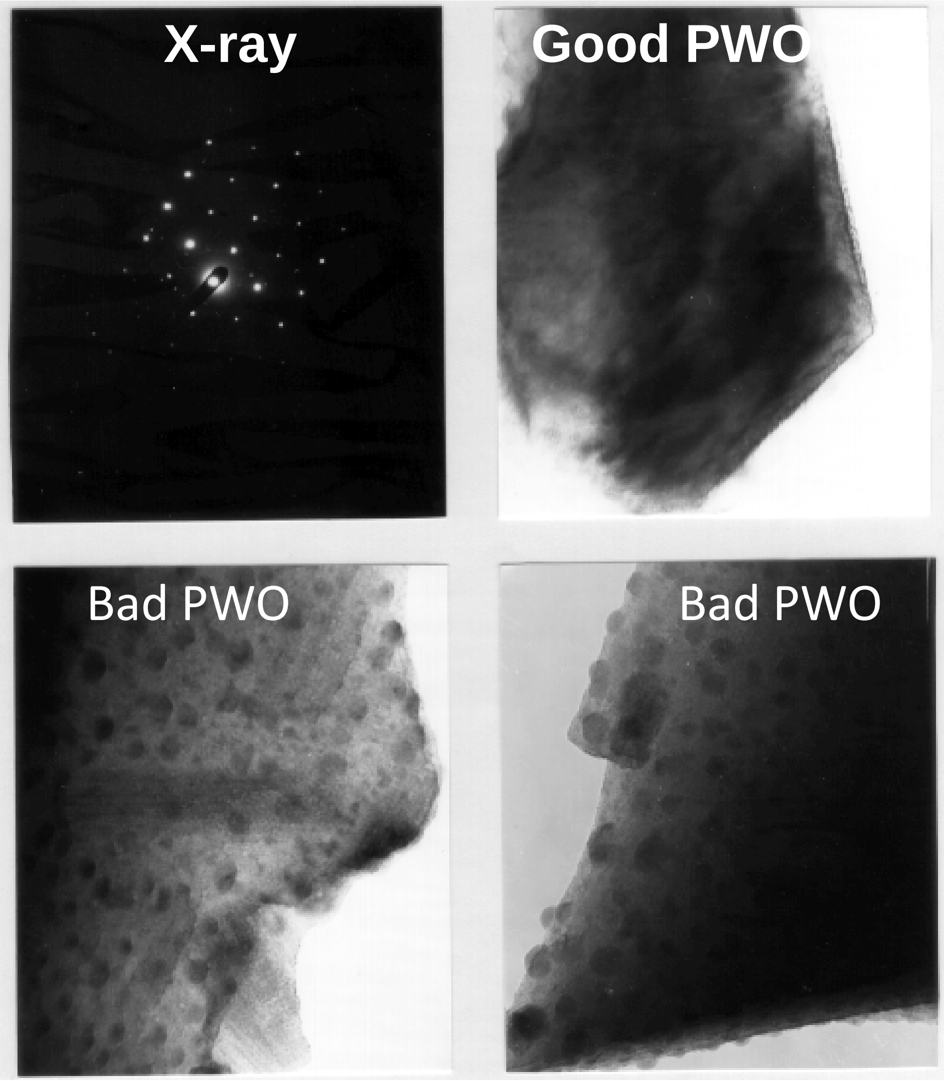
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of kRad/hr.

$$D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R}$$



Oxygen Vacancies Identified by TEM/EDS

TOPCON-002B scope, 200 kV, 10 uA, 5 to10 nm black spots identified
JEOL JEM-2010 scope and Link ISIS EDS localized Stoichiometry Analysis



NIM A413 (1998) 297

Atomic Fraction (%) in $PbWO_4$

As Grown Sample

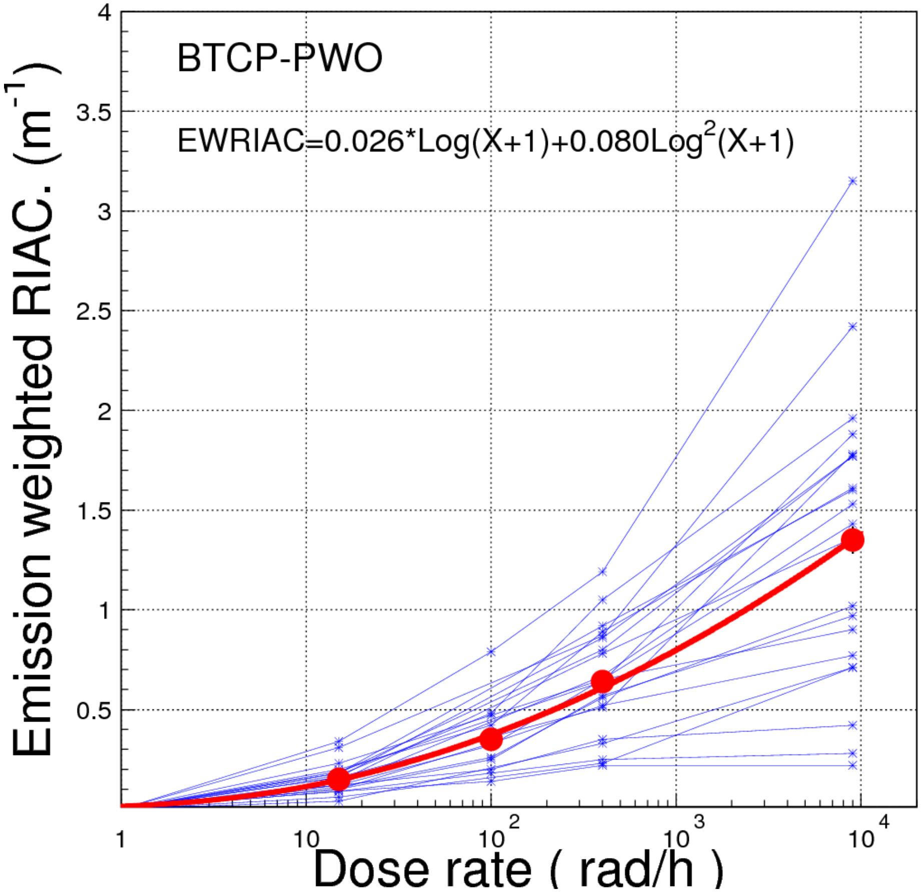
Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

The Same Sample after Oxygen Compensation

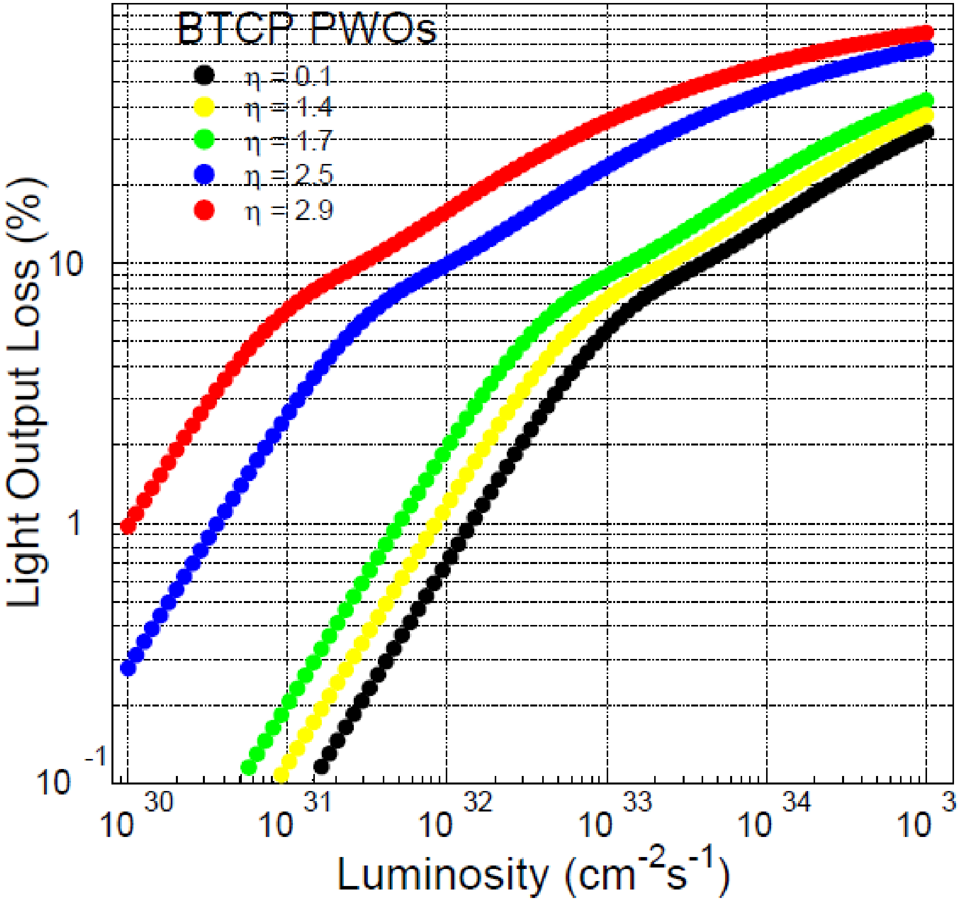
Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

Prediction of PWO Radiation Damage

IEEE Trans. Nucl. Sci. NS-51 1777 (2004)



Talk in CMS Forward Calorimeter Taskforce Meeting, CERN, 12/10/2010

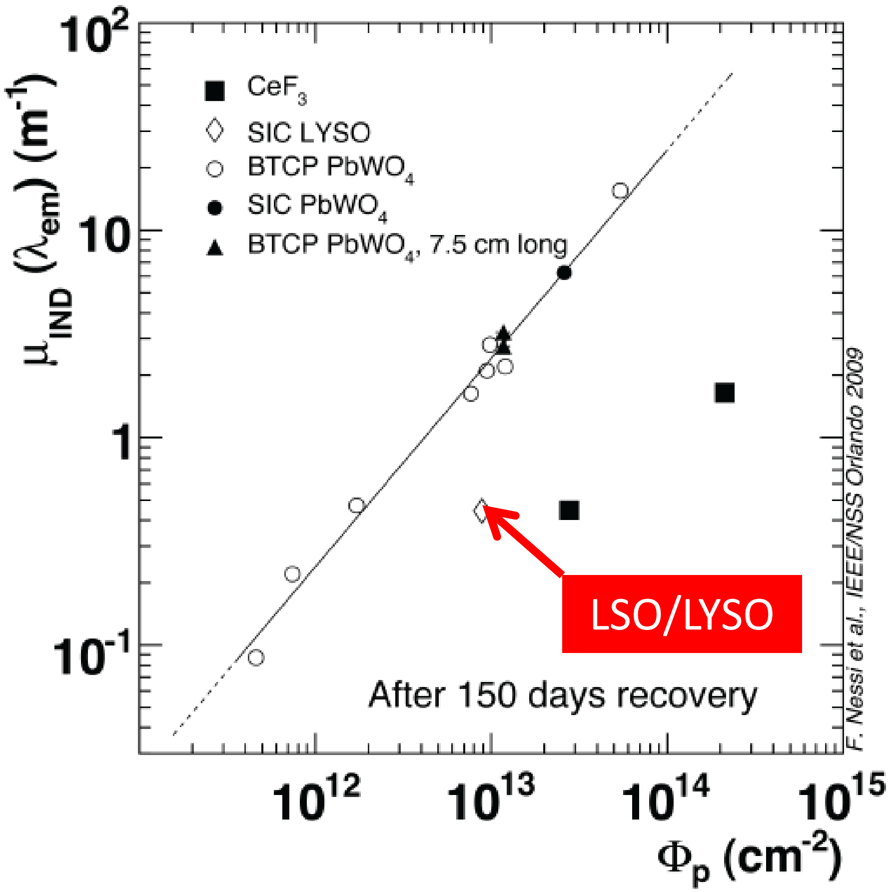


Predicted EM dose induced damage agrees well with the LHC data

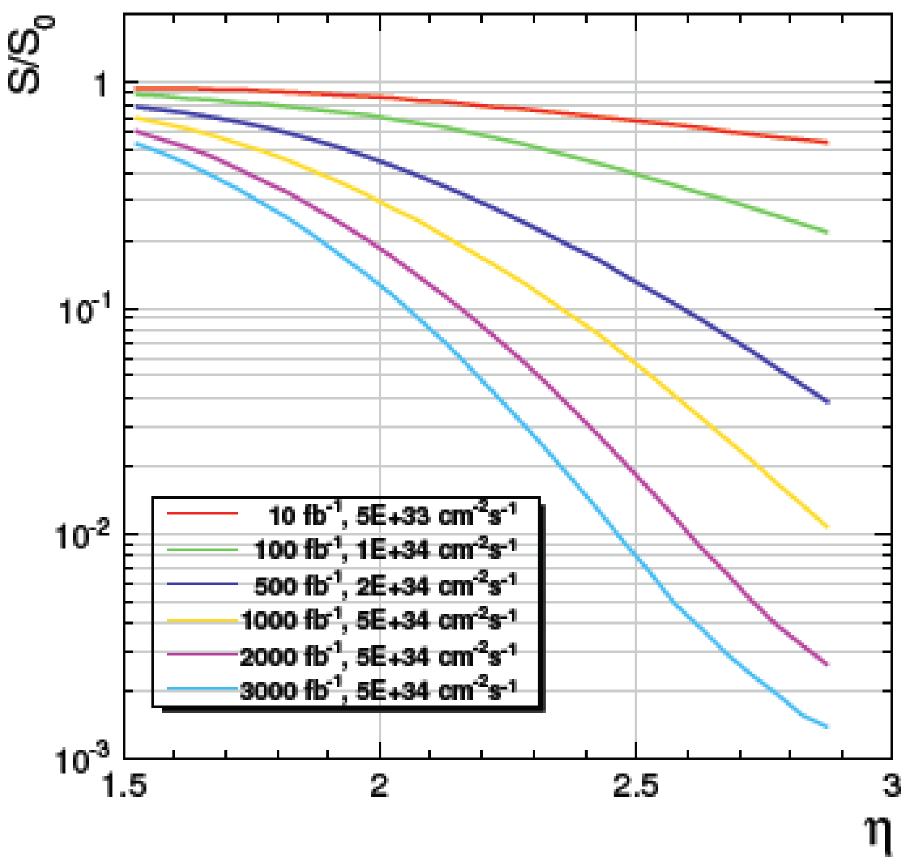
In addition, there is cumulative hadron induced damage in PWO

Proton Induced Damage

G. Dissertori et al., IEEE NSS09, N32-3



Expected LO loss for CMS endcap PWO



The proton induced absorption in LYSO is 1/5 of PWO
Net effect of damage is smaller for **short light path**

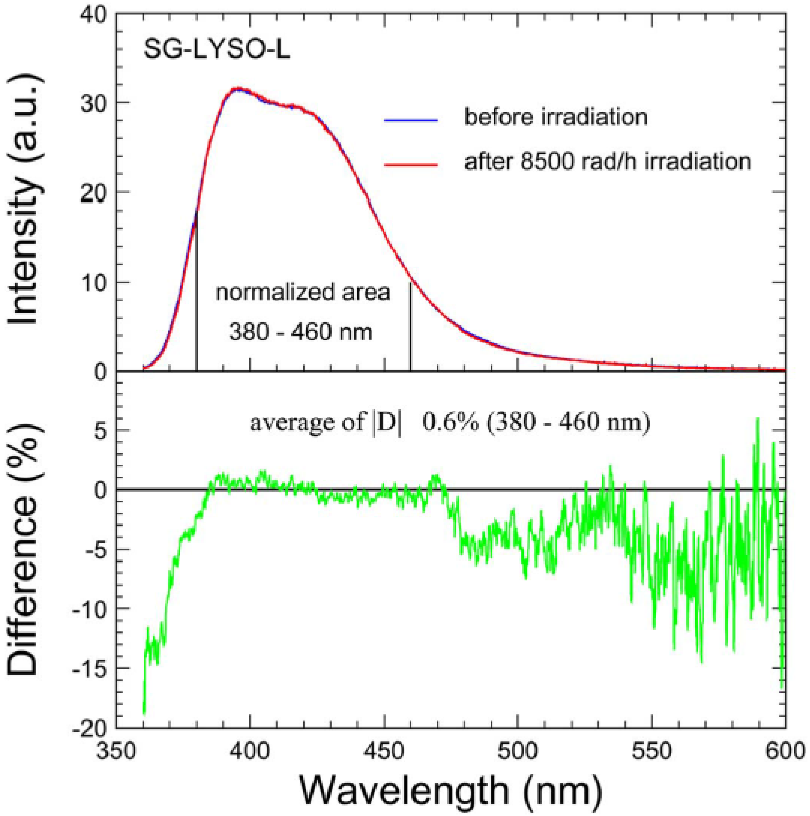
Bright, Fast Scintillator: LSO/LYSO

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (°C)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	26	650 0.9	300	40	30 10	?
Light Yield [b,c] (%)	100	165	3.7	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV	(GEM) TAPS Mu2e	L3 BELLE	(Mu2e) (SuperB) HL-LHC	CMS ALICE PANDA	HHCAL?

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

Bright, Fast & Rad Hard LSO/LYSO

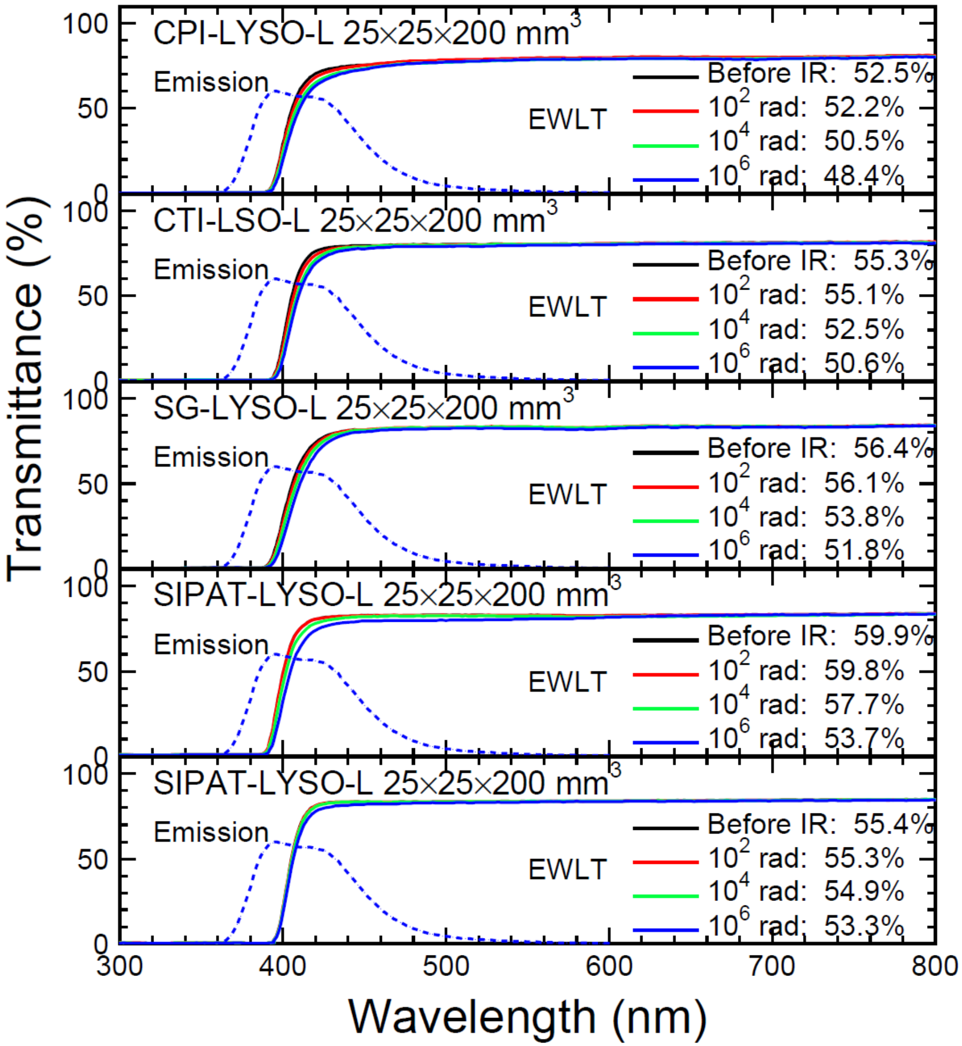
LSO/LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator. The longitudinal non-uniformity issue caused by tapered crystal geometry, self-absorption and cerium segregation can be addressed by roughening one side surface. The material is widely used in the medical industry. Existing mass production capability would help in crystal cost control.

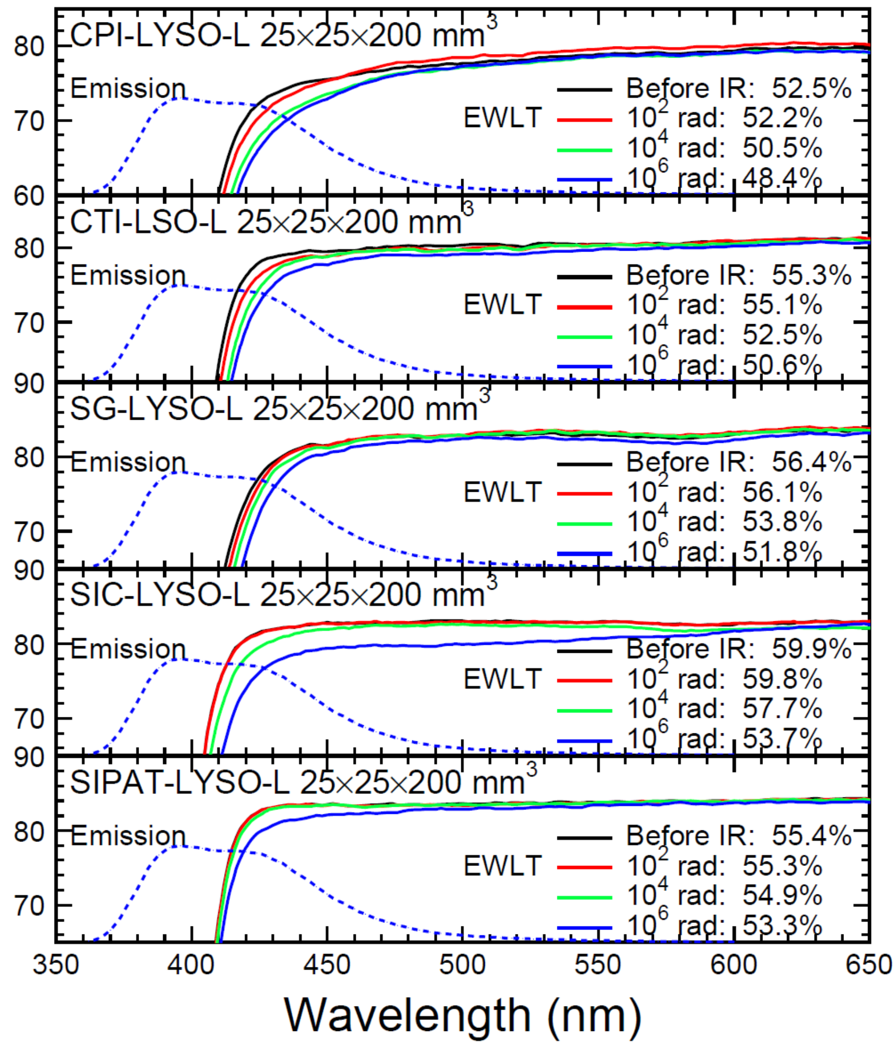


Excellent Radiation Hardness in LT

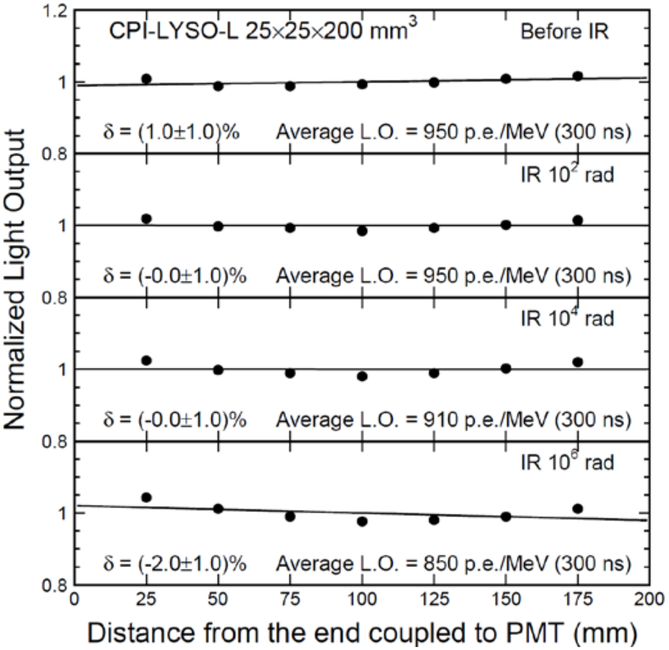
Consistent & Small Damage in LT

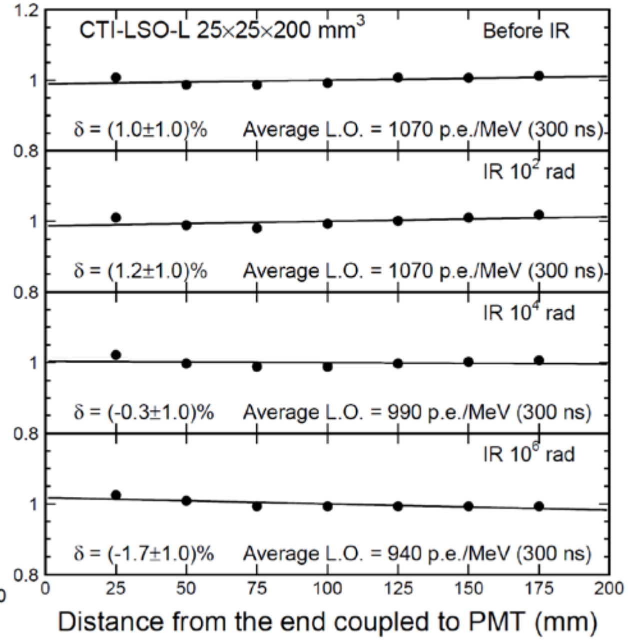
Larger variation @ shorter λ

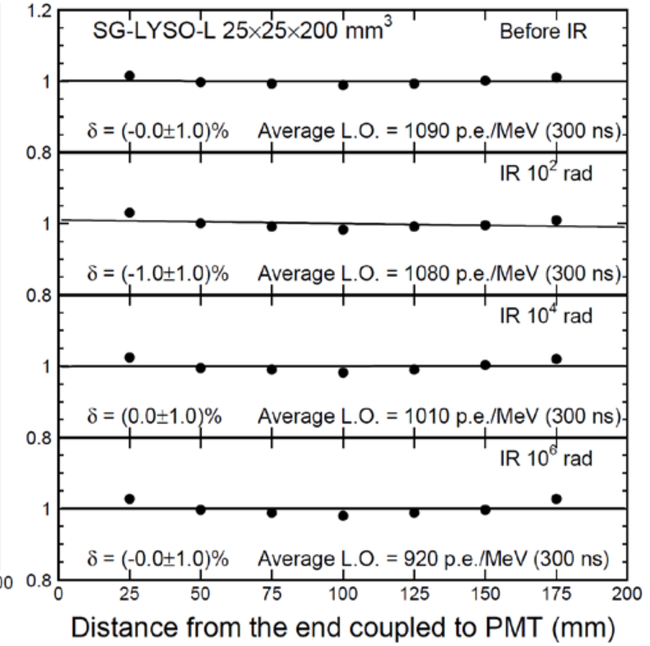


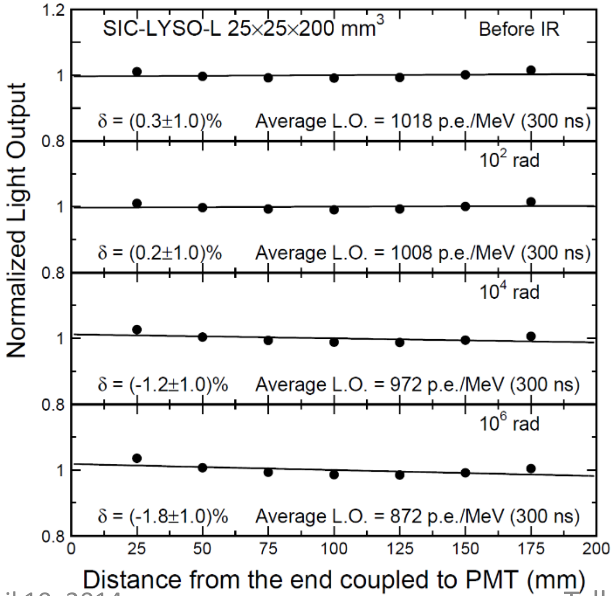


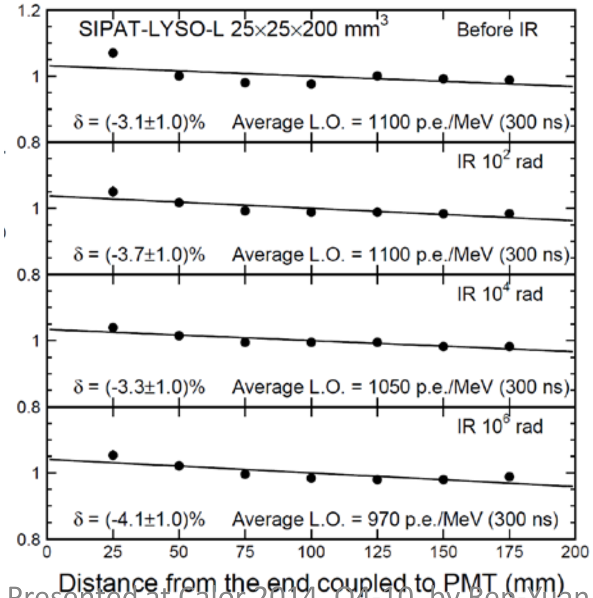
Excellent Radiation Hardness in LO





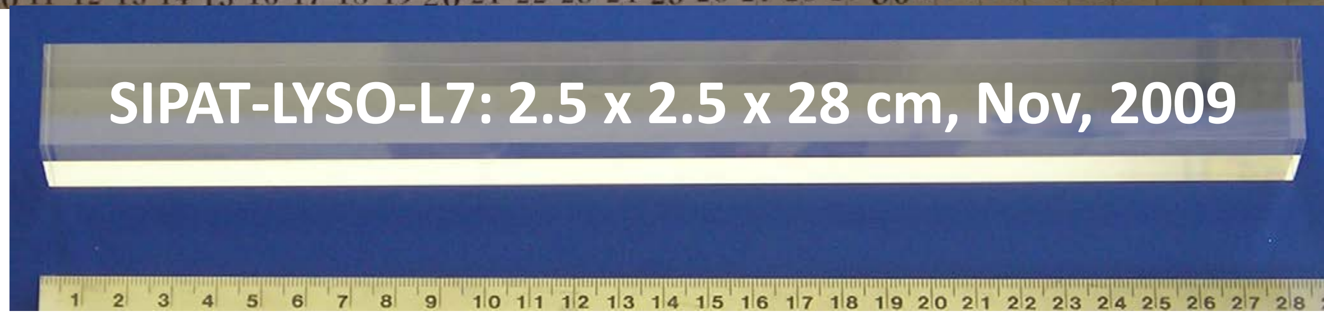


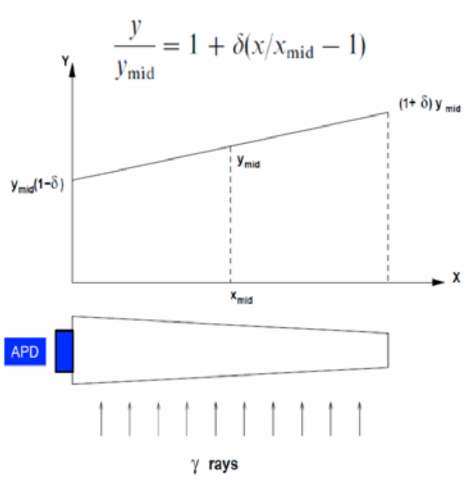


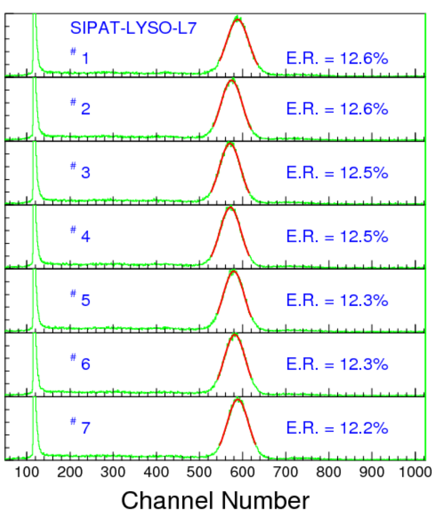


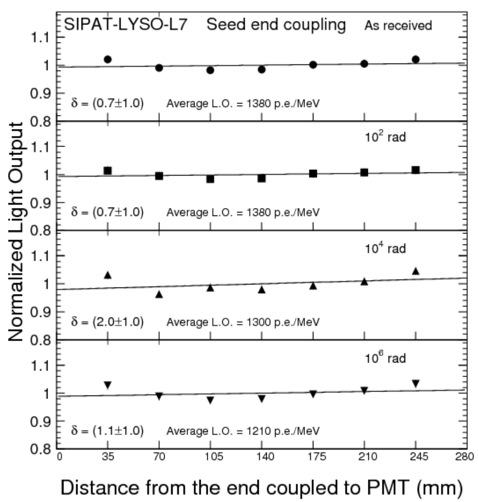
About 12% LO loss observed after 1 Mrad irradiation in all samples with LRU maintained. It can be corrected by light monitoring.

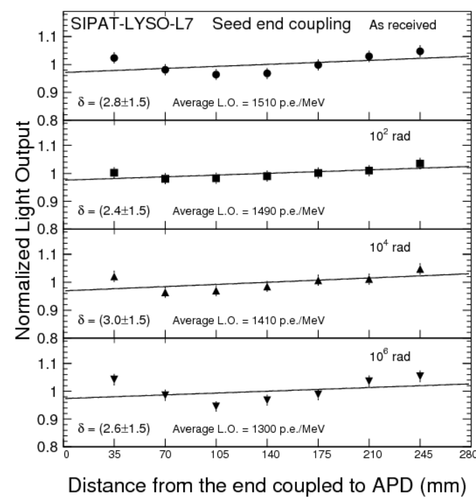
28 cm Long LYSO Under γ-Rays





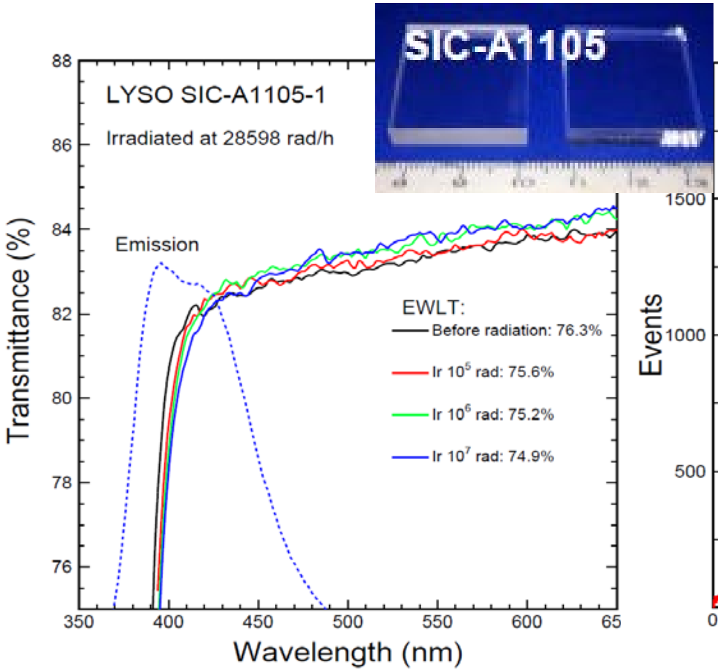


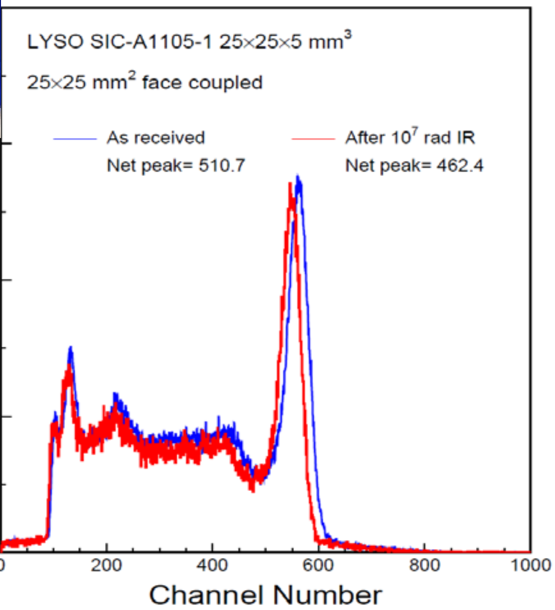


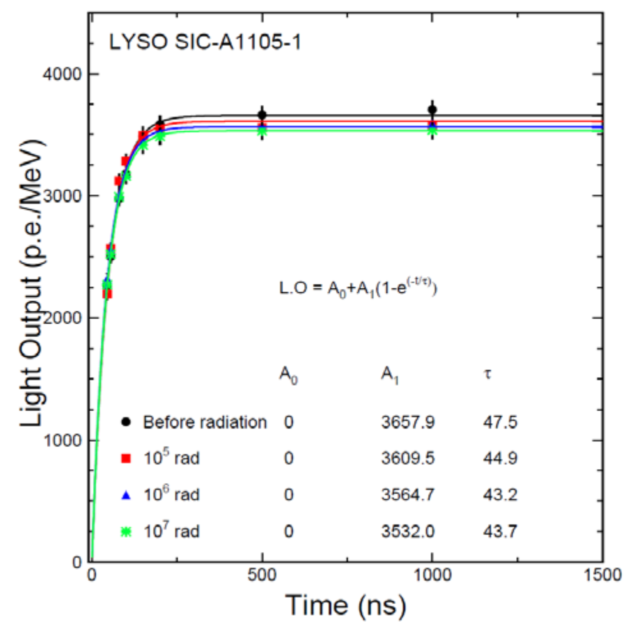


Damage in 2 x 2 x 0.5 cm Plates

5 mm thick LYSO plates show degradation of a few percepts up to 10 Mrad

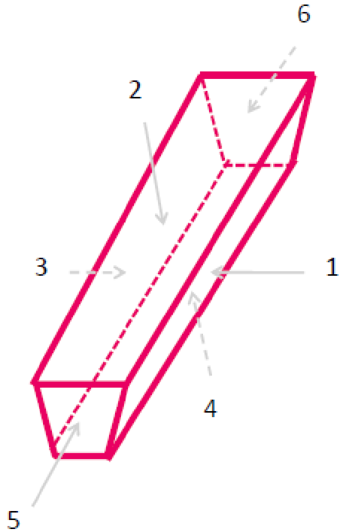


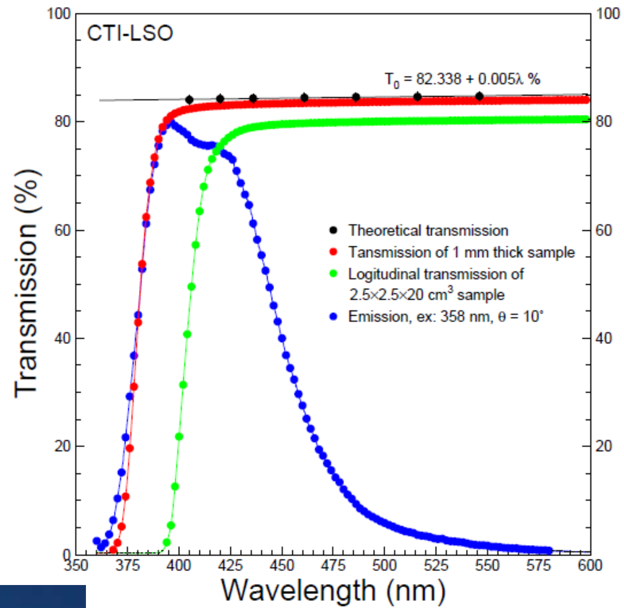


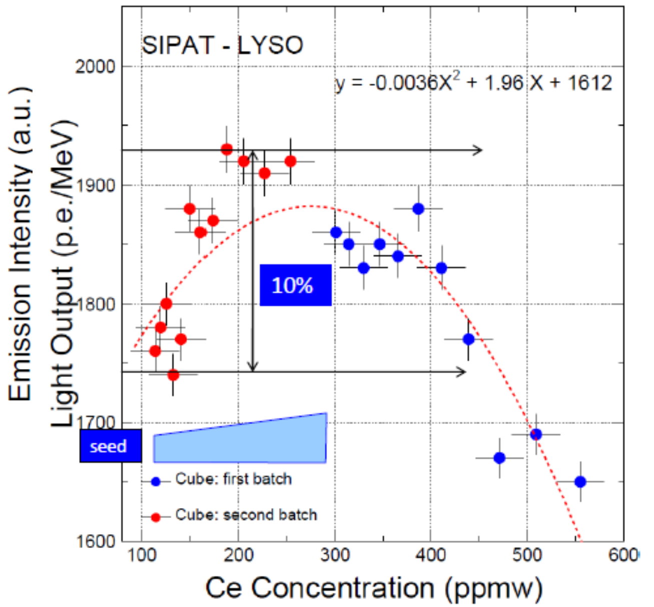


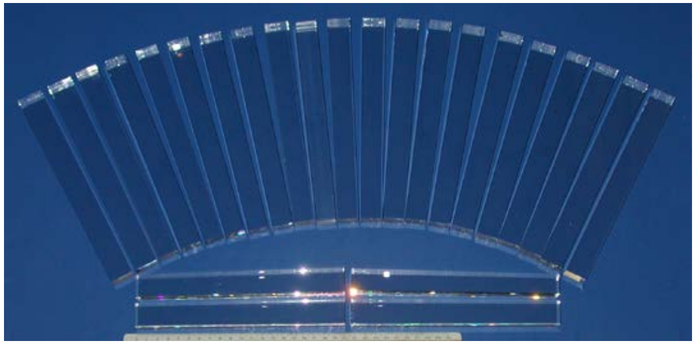
Samples	EWLT (%)	L.O. (p.e./MeV)	EWLT loss (%)			L.O. loss (%)		
			10^5 rad	10^6 rad	10^7 rad	10^5 rad	10^6 rad	10^7 rad
SIC-A1105-1	76.3	3657.9	0.9	1.4	1.8	1.3	2.5	3.4

LYSO Light Response Uniformization

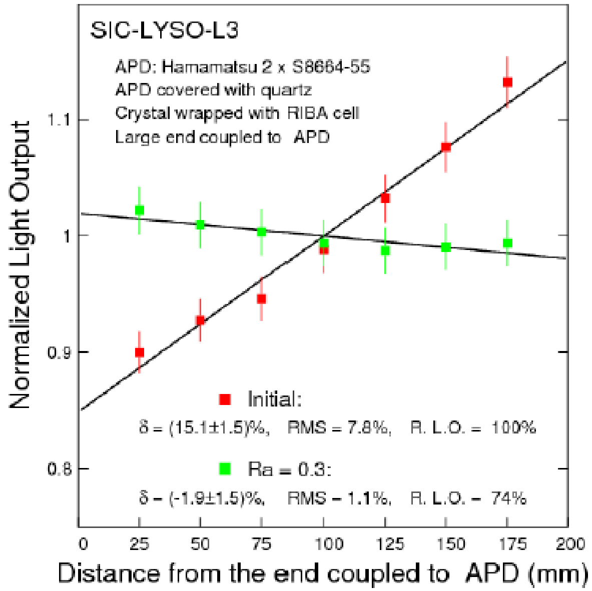


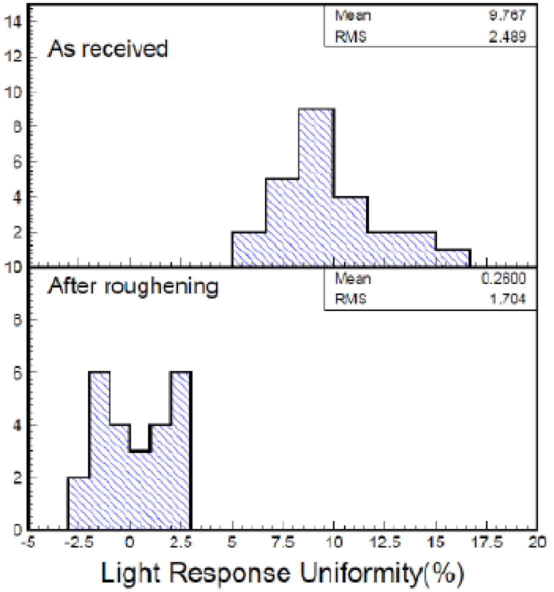




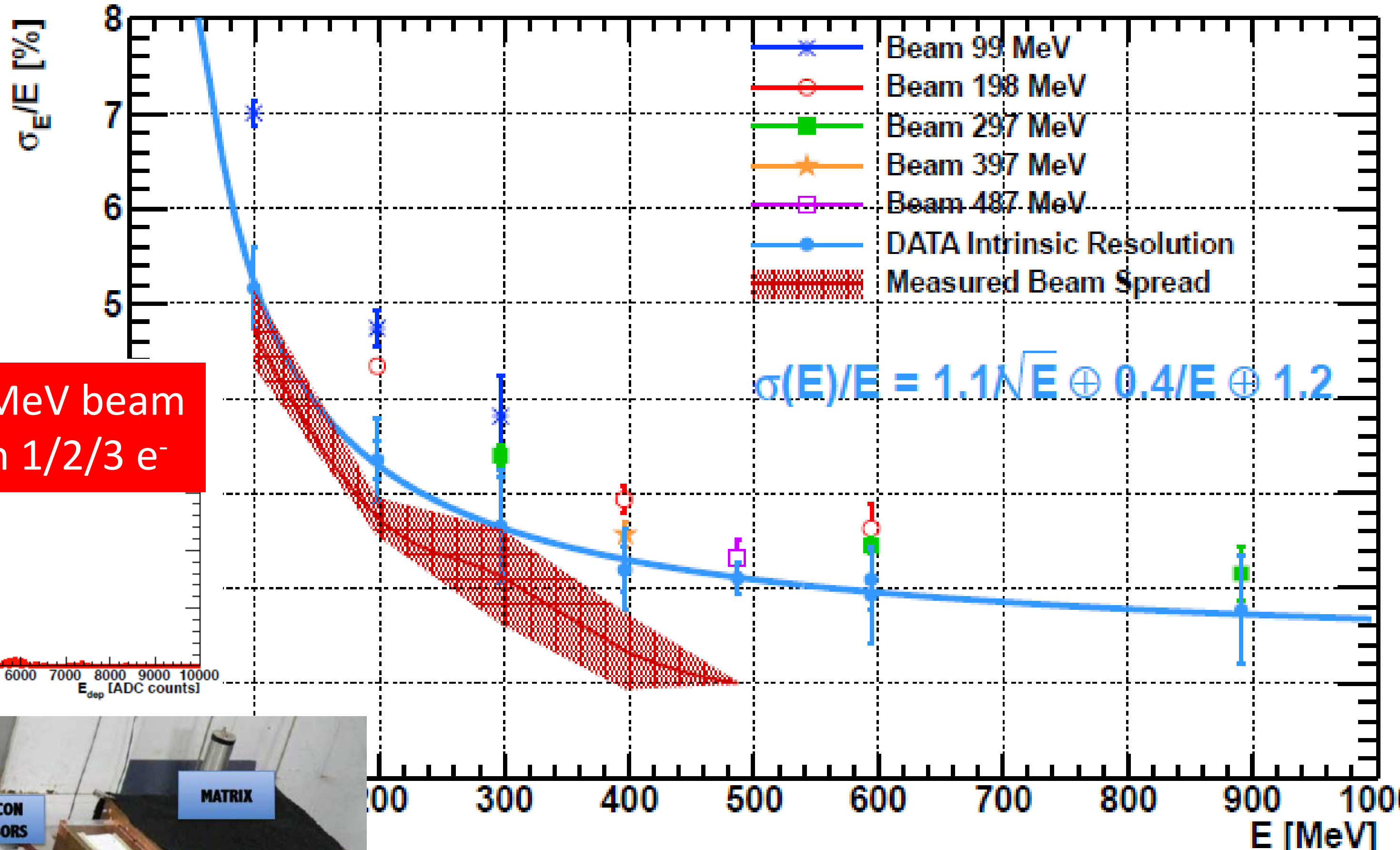


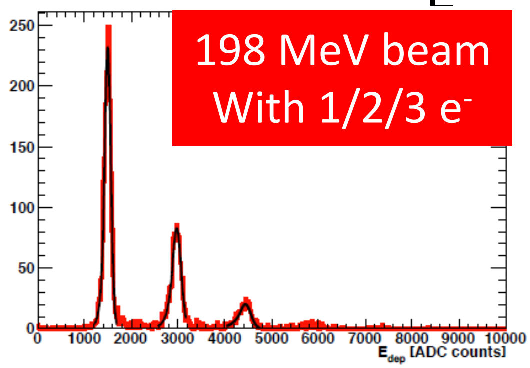
25 LYSO test beam crystals are uniformized to |δ| < 3% by roughening the smallest side surface.

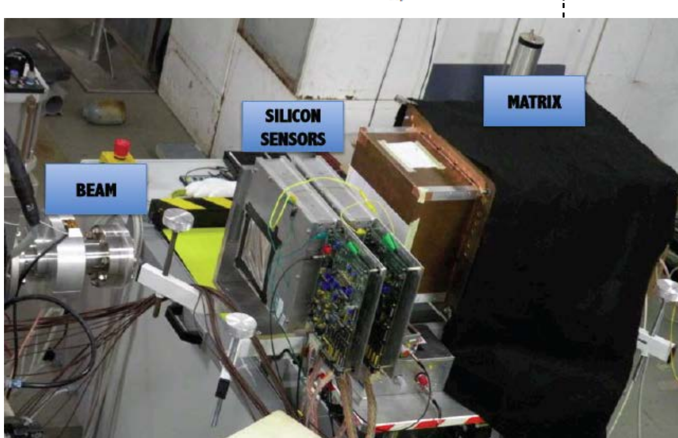




SuperB LYSO Test Beam Result

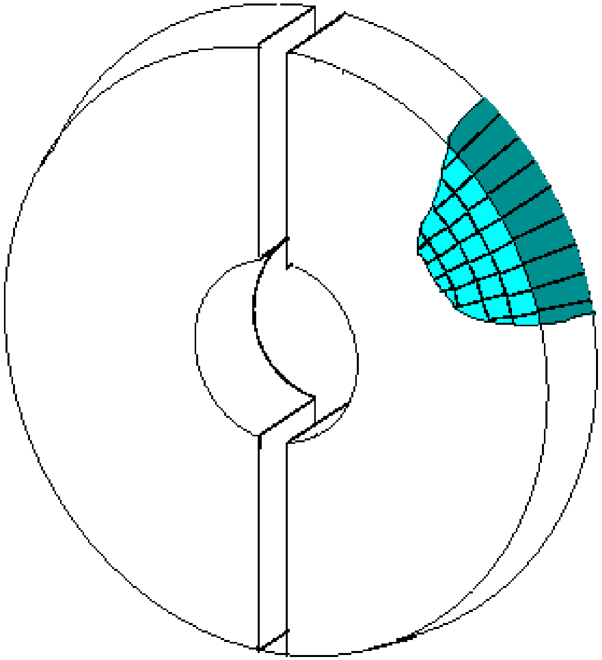


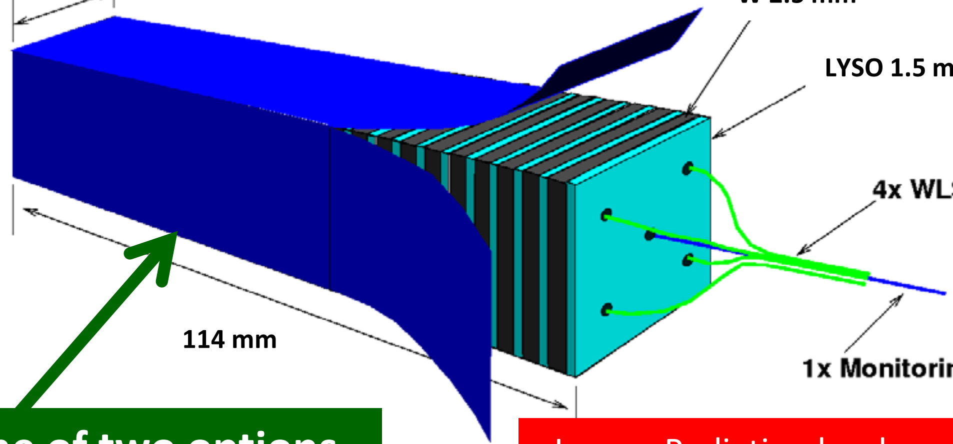




$$\frac{\sigma(E)}{E} = \frac{1.1}{\sqrt{E[GeV]}} \oplus \frac{0.4}{E[GeV]} \oplus 1.2\ \%$$

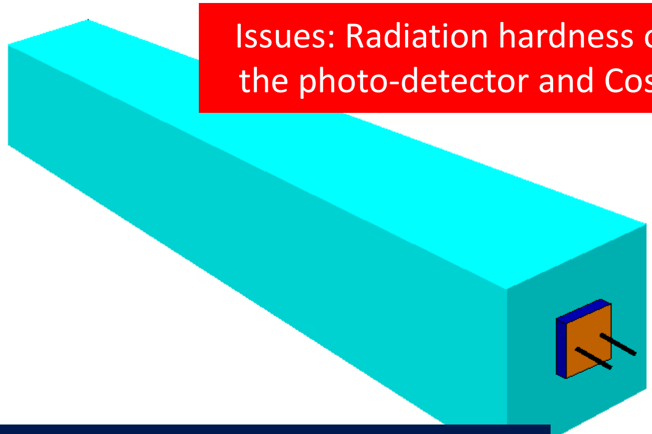
Option for CMS FCAL Upgrade



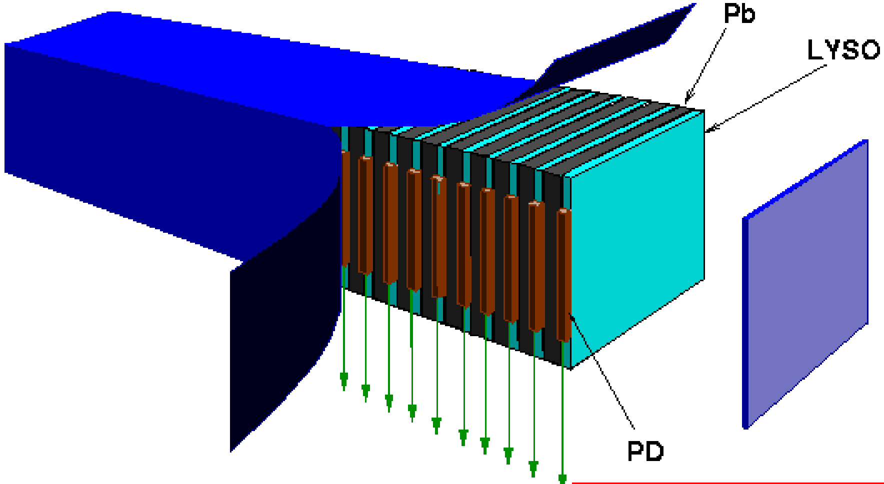


One of two options for CMS Upgrade TR

Issues: Radiation hardness of photo-detector and WLS fiber



Issues: Radiation hardness of the photo-detector and Cost

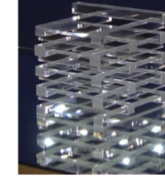


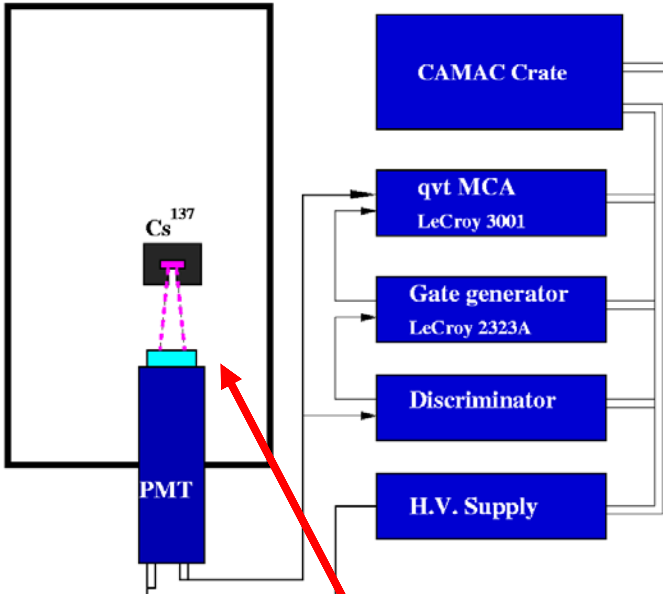
CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 3 m^3

Reduced Crystal Cost

Issue: Radiation hardness of the photo-detector

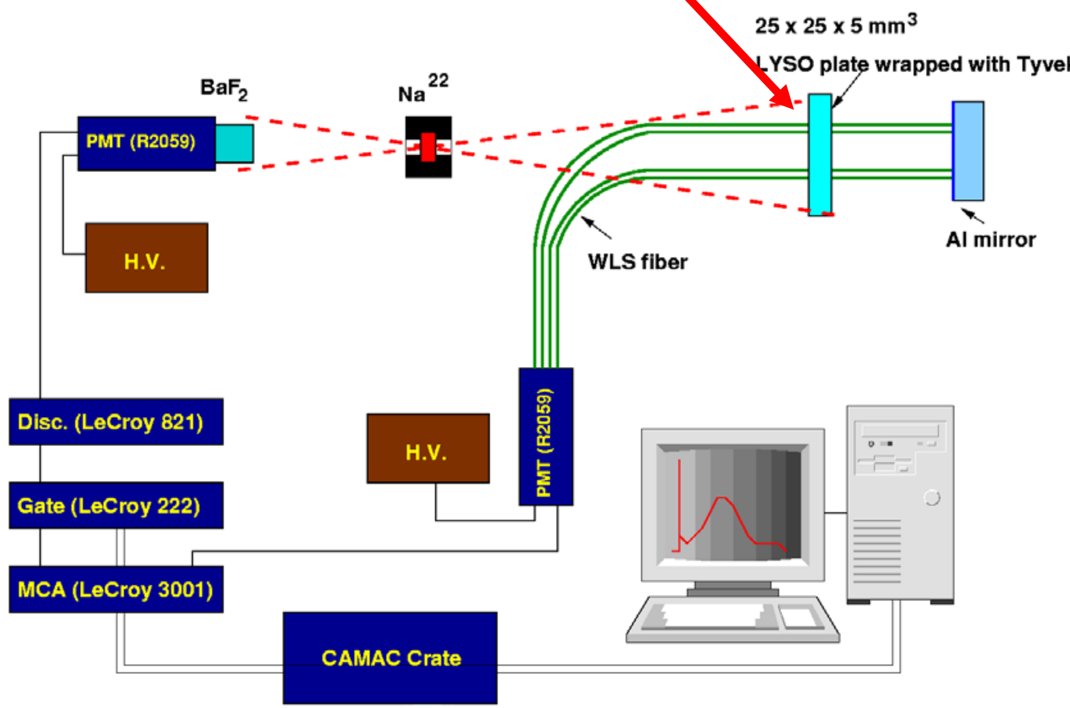
Two Measurement Setups





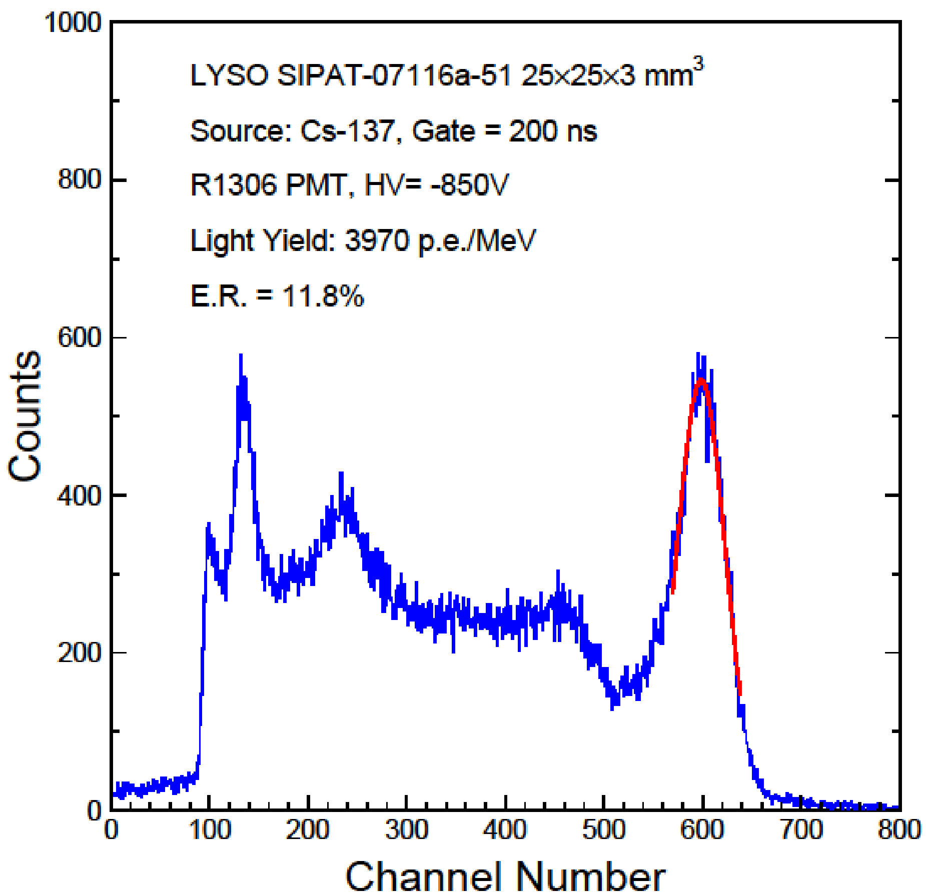
1) LYSO plates with Tyvek wrapping are readout directly by a R1306 PMT using a Cs-137 γ-ray source.

2) LYSO plates with Tyvek wrapping are readout with four Y11 WLS fibers of 40 cm long and a R2059 PMT using a Na-22 γ-ray source and coincidence.

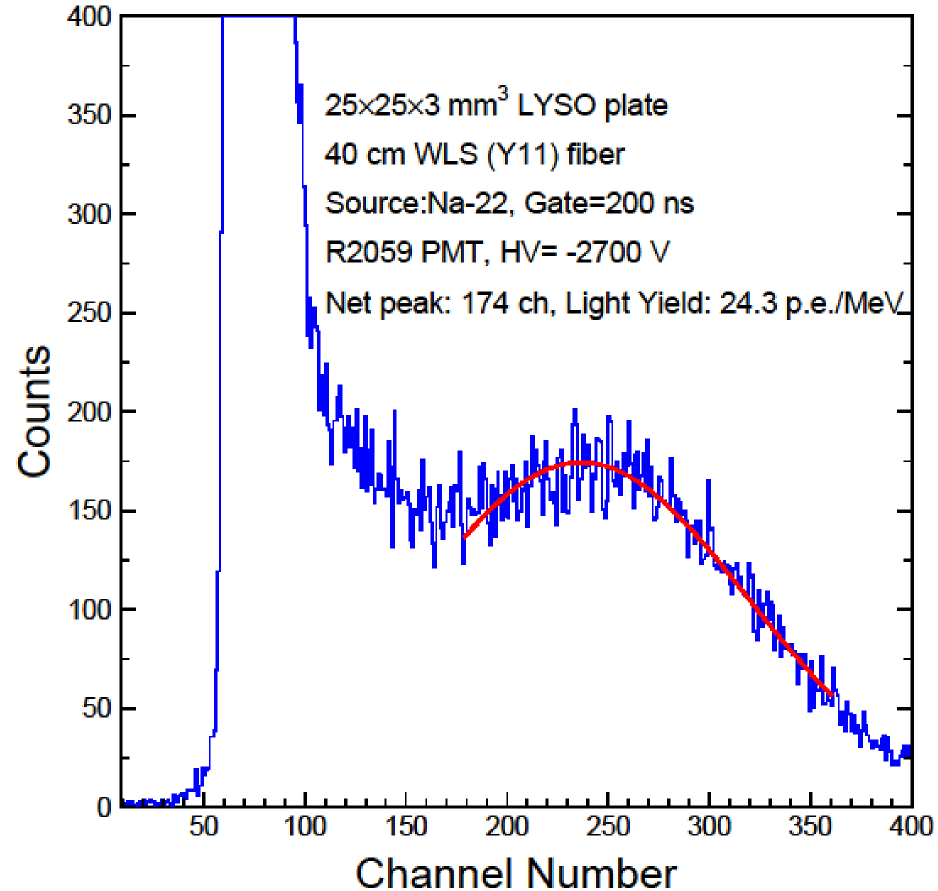


PHS of 3 mm LYSO Plate

LYSO 25 × 25 × 3 mm^3

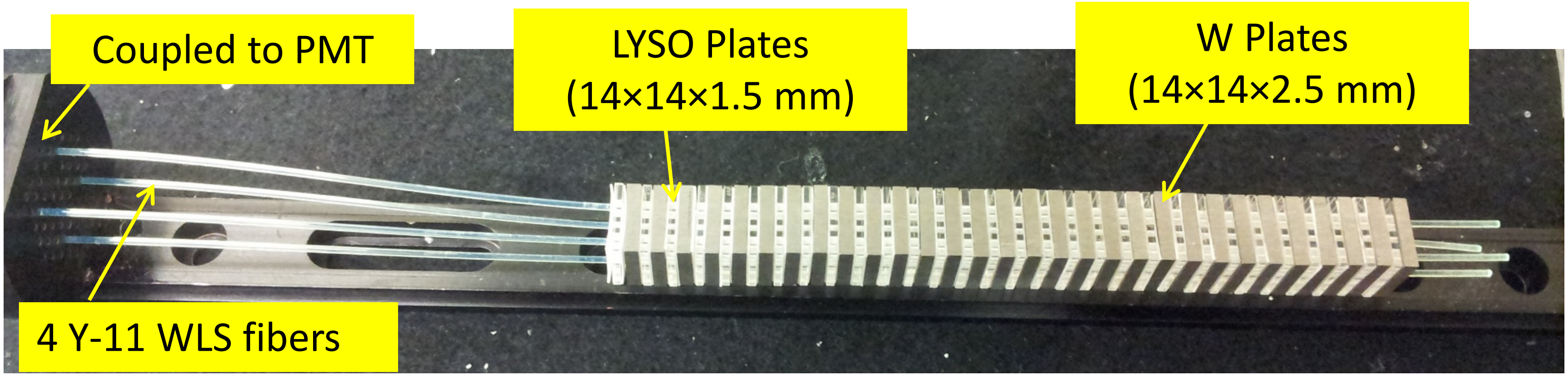


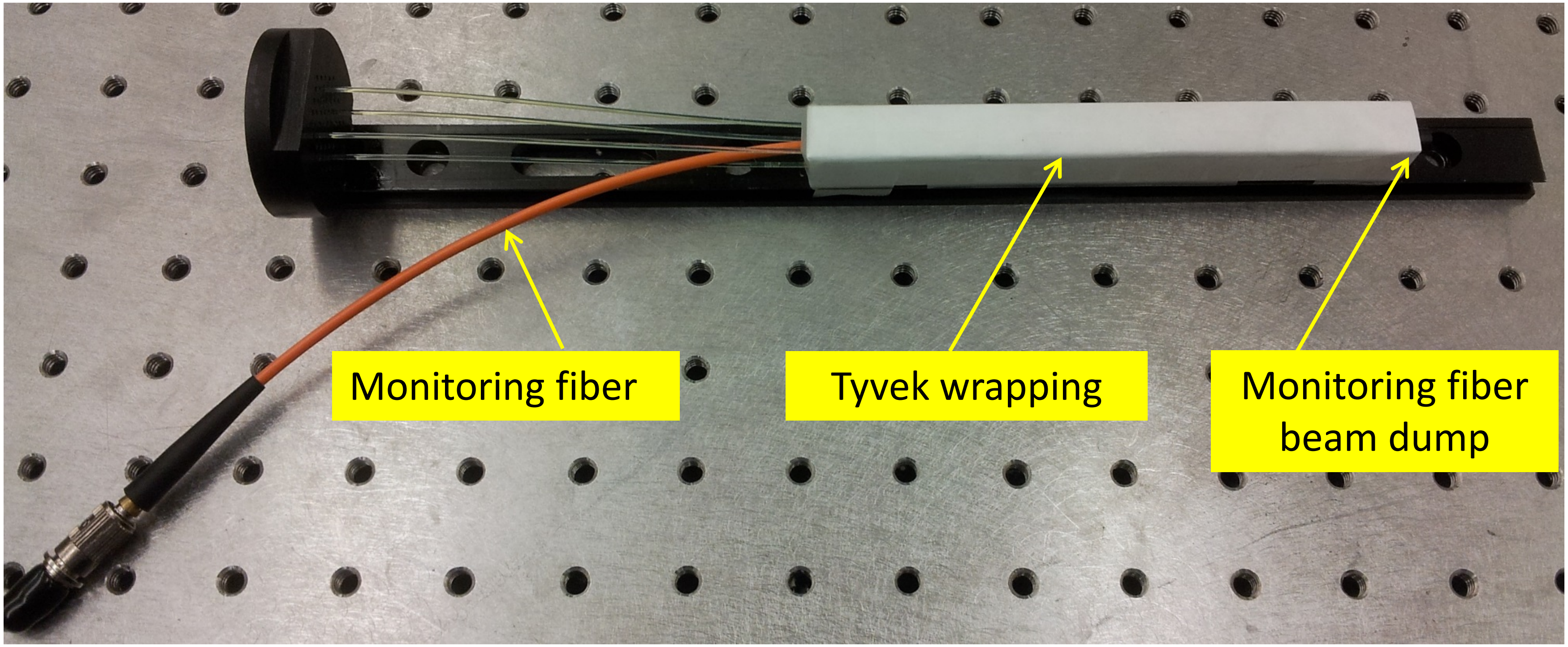
3 mm plate & 4 x 40 cm Y11 fiber



About 1% light collected via WLS

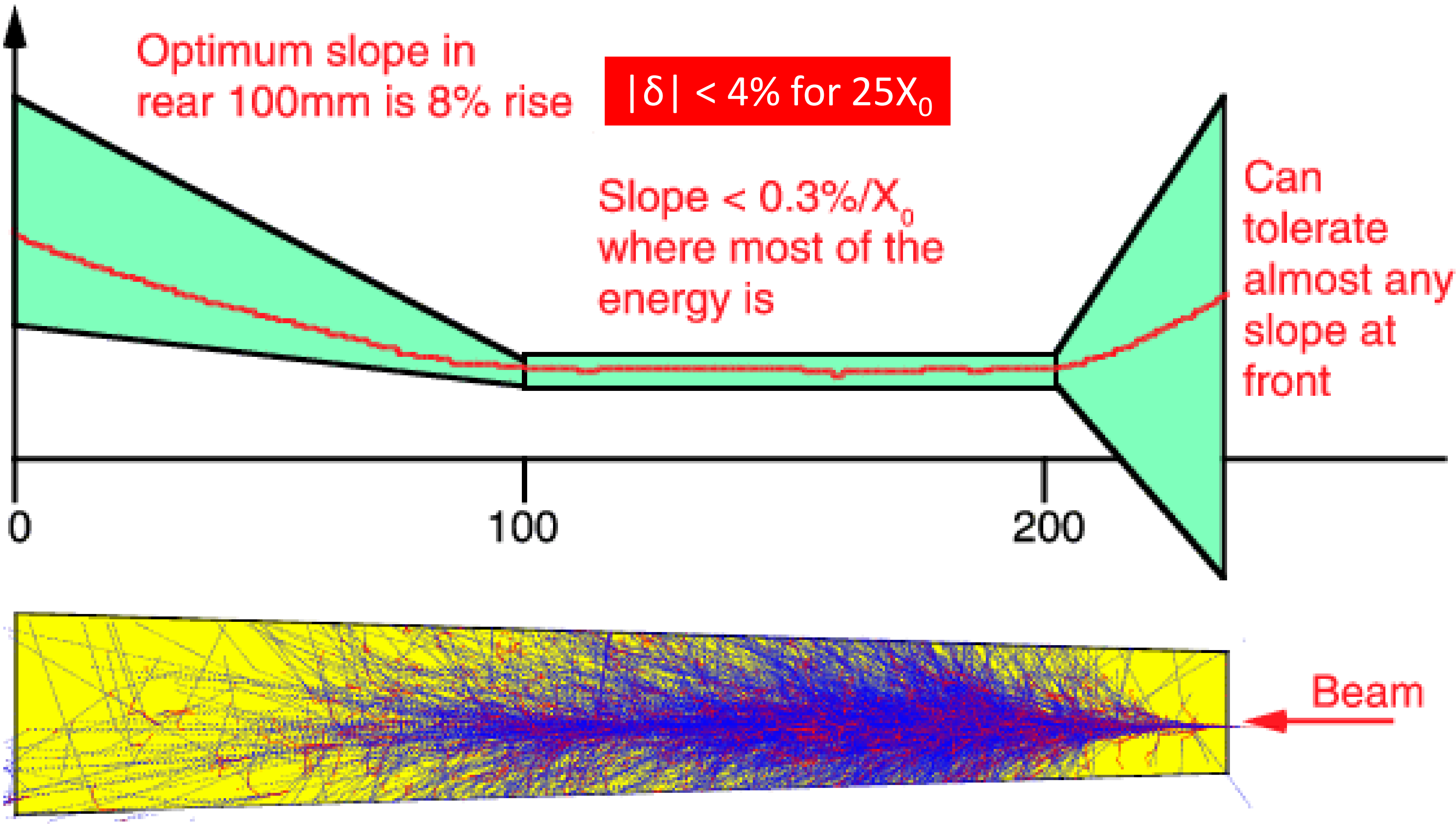
Shashlik Tower Assembly



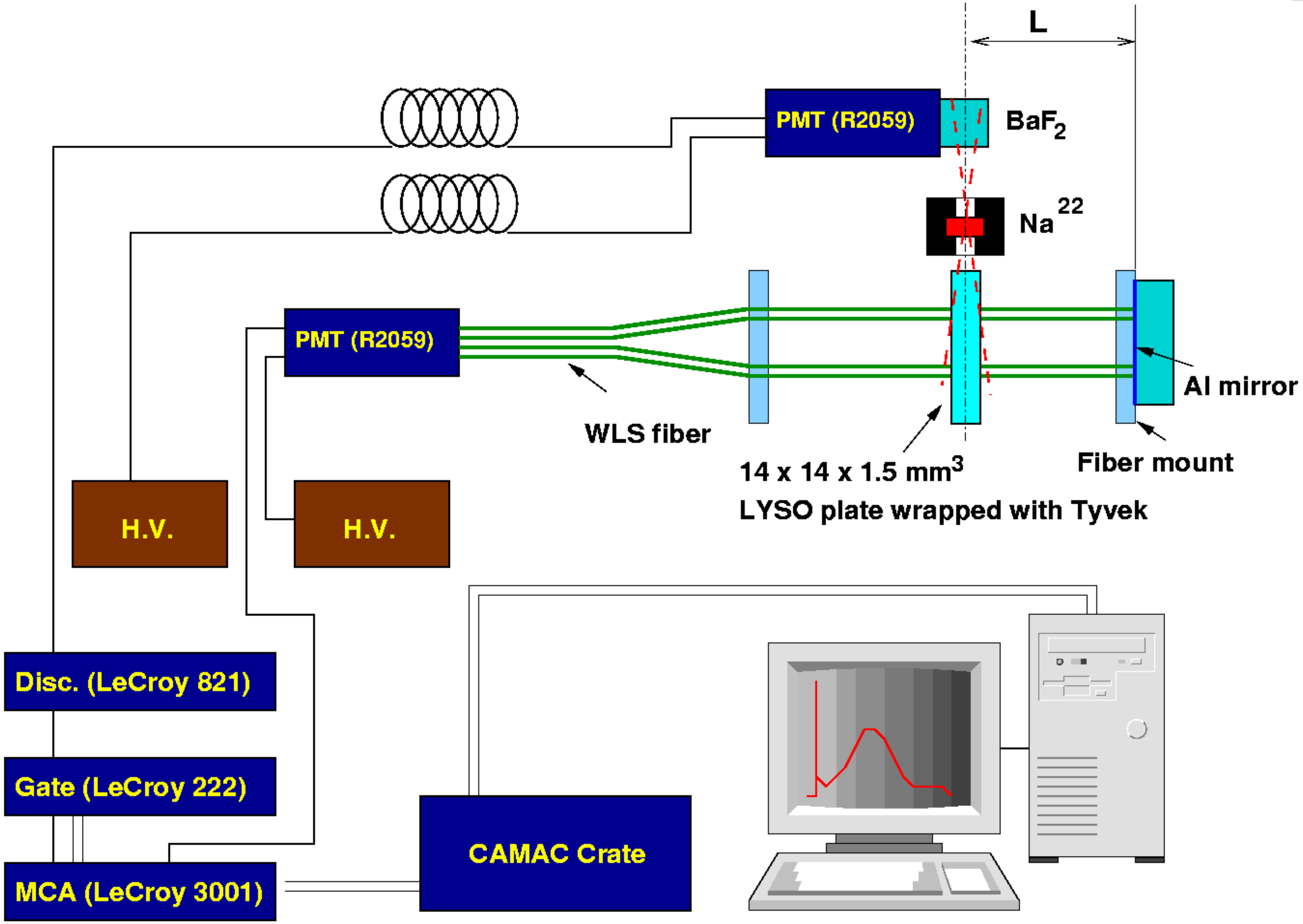


CMS Specification for Uniformity

D. Graham & C. Seez, CMS Note 1996-002

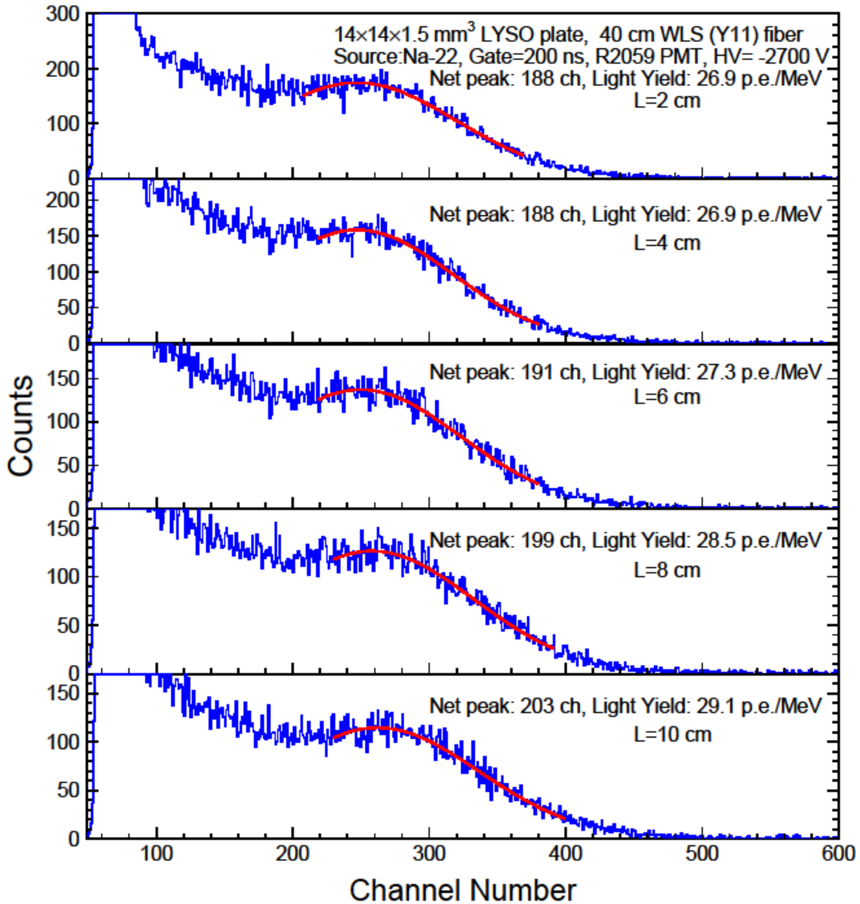


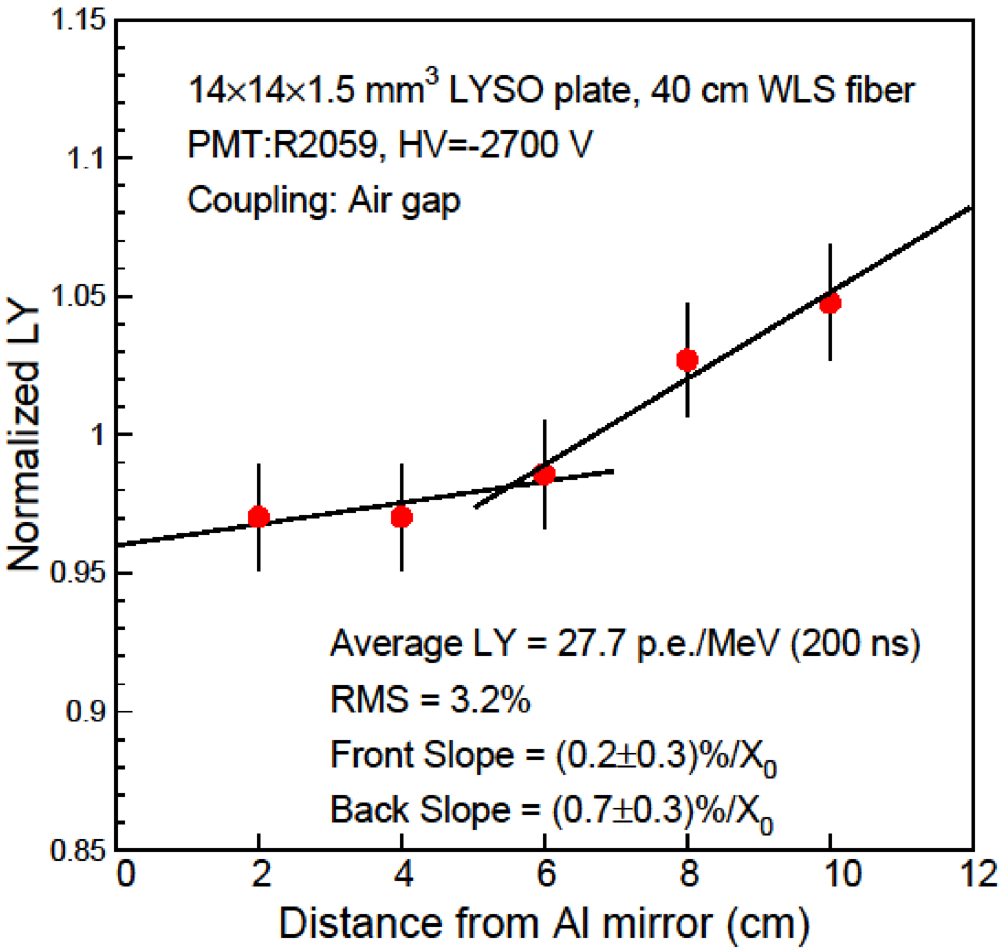
LYSO/W Response Uniformity



LYSO/W Shashlik Uniformity

Front: 0.2%/X_0, Back: 8% rise





Alternative Fast Crystals

Talk in CMS Forward Calorimetry Task Force Meeting, CERN, June 27, 2012

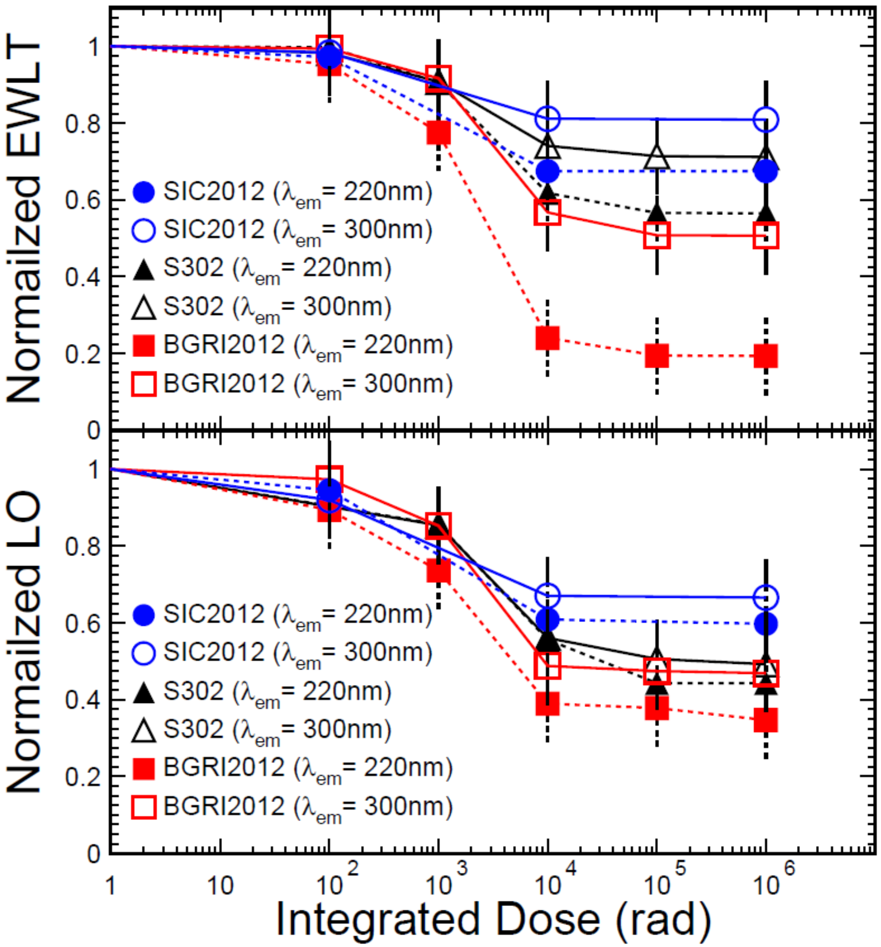
	LSO/LYSO	GSO	YSO[1]	CsI	BaF_2	CeF_3	$CeBr_3$[2]	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404)[3]
Density (g/cm^3)	7.40	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70[#]
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.70	1.96	2.81	1.88	42.54
Molière Radius (cm)	2.07	2.23	2.93	3.57	3.10	2.41	2.97	3.71	2.85	9.59
Interaction Length (cm)	20.9	22.2	27.9	39.3	30.7	23.2	31.5	37.6	30.4	78.8
Z value	64.8	57.9	33.3	54.0	51.6	50.8	45.6	47.3	45.6	-
dE/dX (MeV/cm)	9.55	8.88	6.56	5.56	6.52	8.42	6.65	5.27	6.90	2.02
Emission Peak[a] (nm)	420	430	420	420 310	300 220	340 300	371	335	356	408
Refractive Index[b]	1.82	1.85	1.80	1.95	1.50	1.62	1.9	1.9	1.9	1.58
Relative Light Yield[a,c]	100	45	76	4.2 1.3	42 4.8	8.6	141	15 49	153	35
Decay Time[a] (ns)	40	73	60	30 6	650 0.9	30	17	570 24	20	1.8
d(LY)/dT[d] (%/°C)	-0.2	-0.4	-0.3	-1.4	-1.9 0.1	~0	-0.1	0.1	0.2	~0

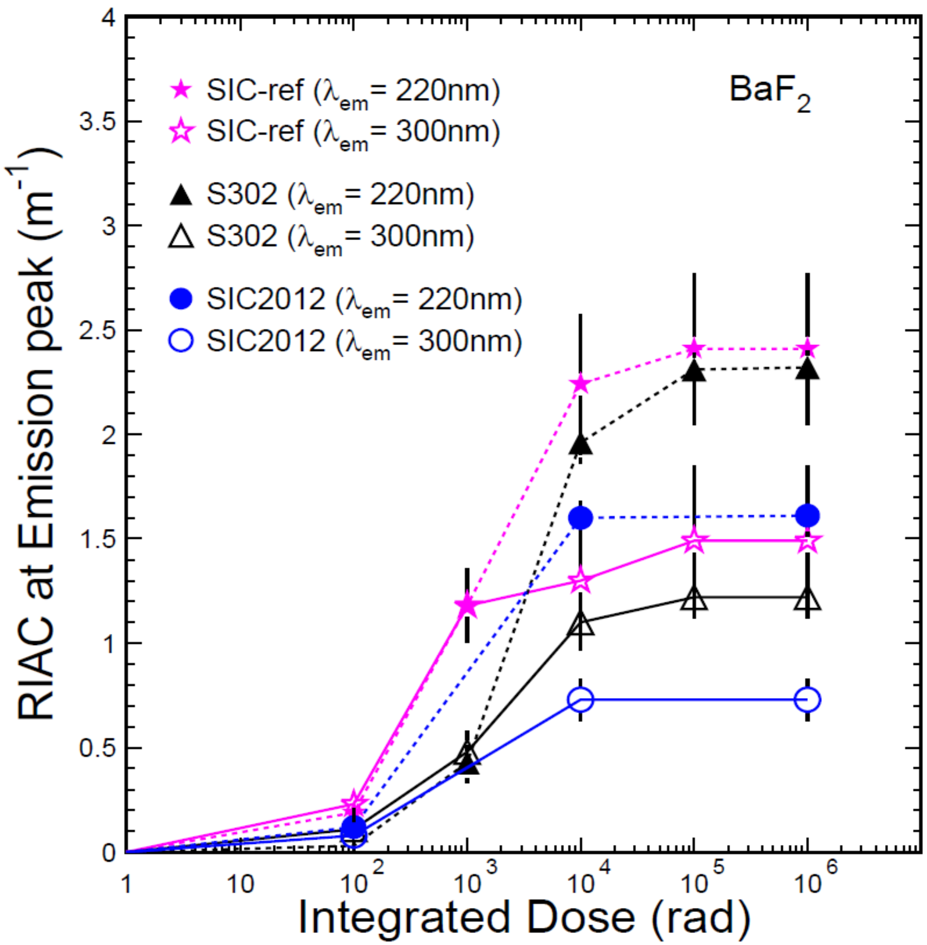
a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. Relative light yield normalized to the light yield of LSO
d. At room temperature (20°C)
#. Softening point

1. N. Tsuchida et al ***Nucl. Instrum. Methods Phys. Res. A,*** 385 (1997) 290-298
   http://www.hitachi-chem.co.jp/english/products/cc/017.html
2. W. Drozdowski et al. ***IEEE TRANS. NUCL. SCI***, VOL.55, NO.3 (2008) 1391-1396
   Chenliang Li et al, ***Solid State Commun***, Volume 144, Issues 5–6 (2007),220–224
   http://scintillator.lbl.gov/
3. http://www.detectors.saint-gobain.com/Plastic-Scintillator.aspx
   http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/216.html

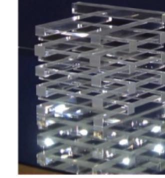
Damage in Long BaF_2 Crystals

Radiation damage in BaF2 crystals saturates at a few tens of krad
SIC2012 is more radiation hard than other samples
Slow component is more radiation hard than the fast component



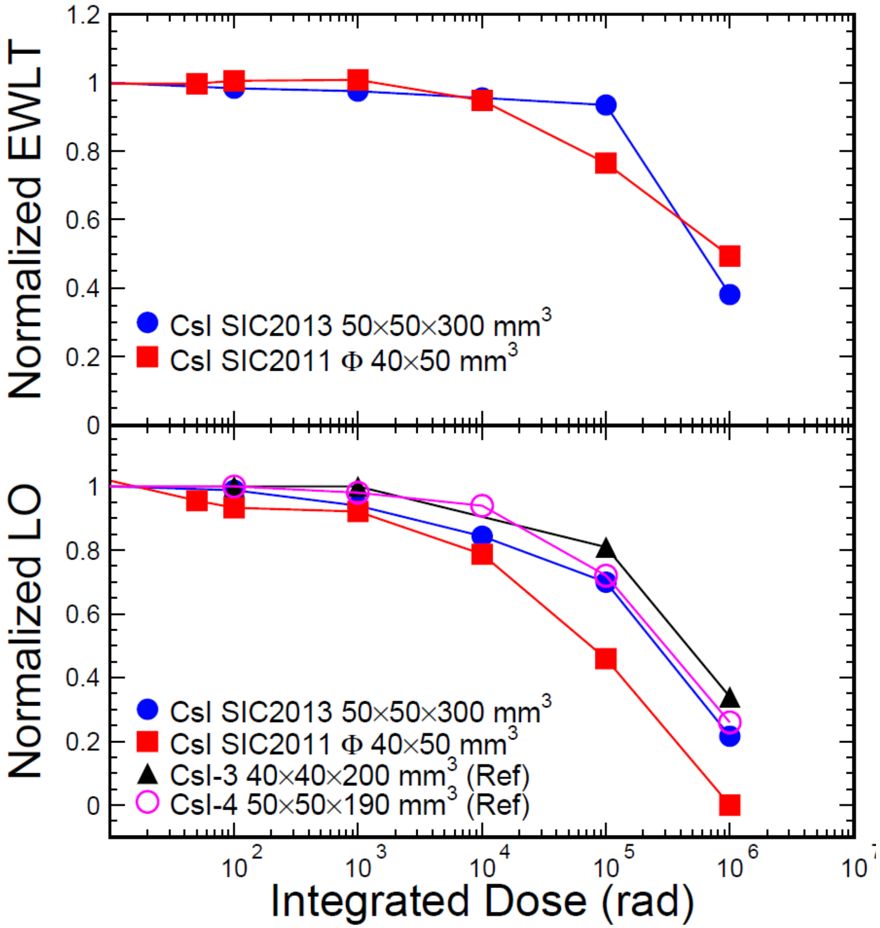


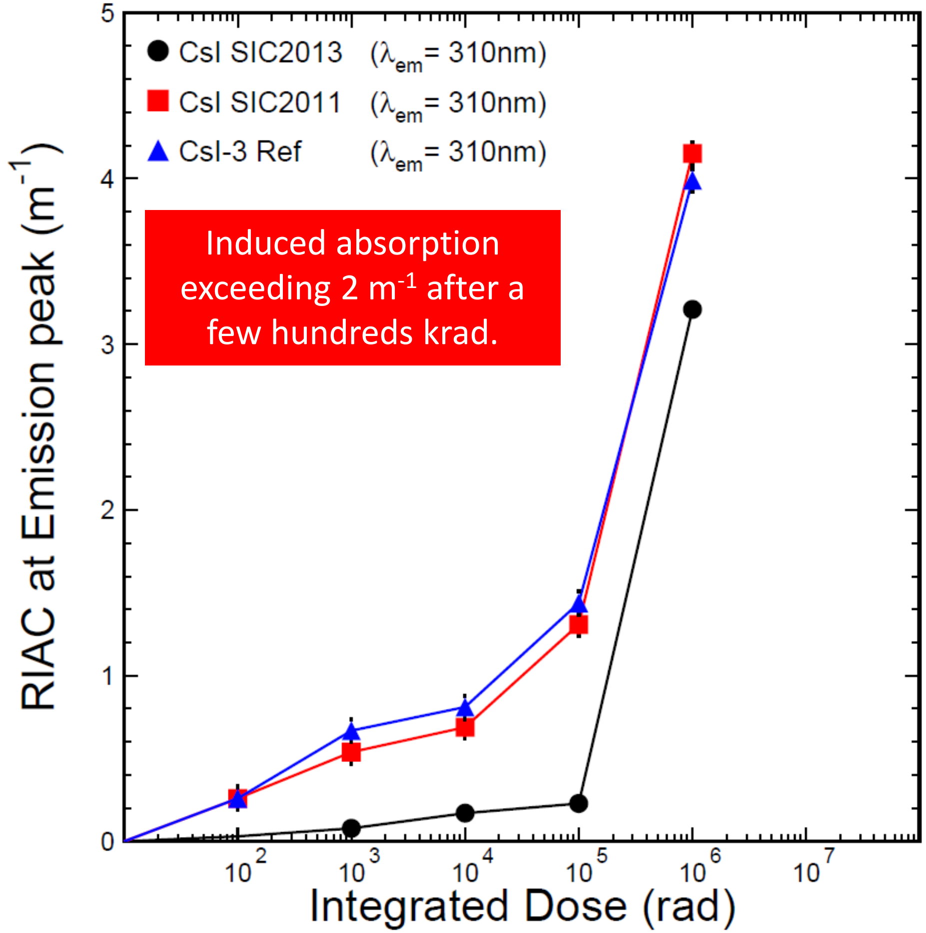
RIAC of mass produced BaF_2 may be controlled to less than 1.6 m^{-1}



Damage in Long Pure CsI Crystals

Consistent damage between 30/20 cm long pure CsI from SIC/Kharkov

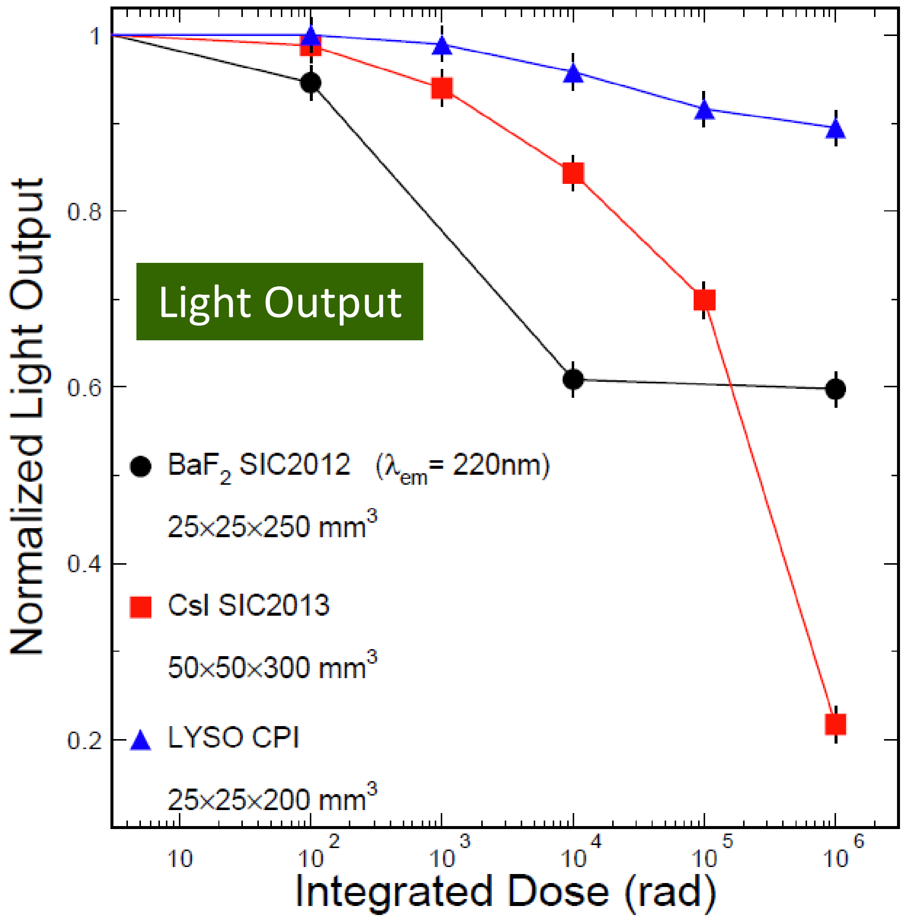


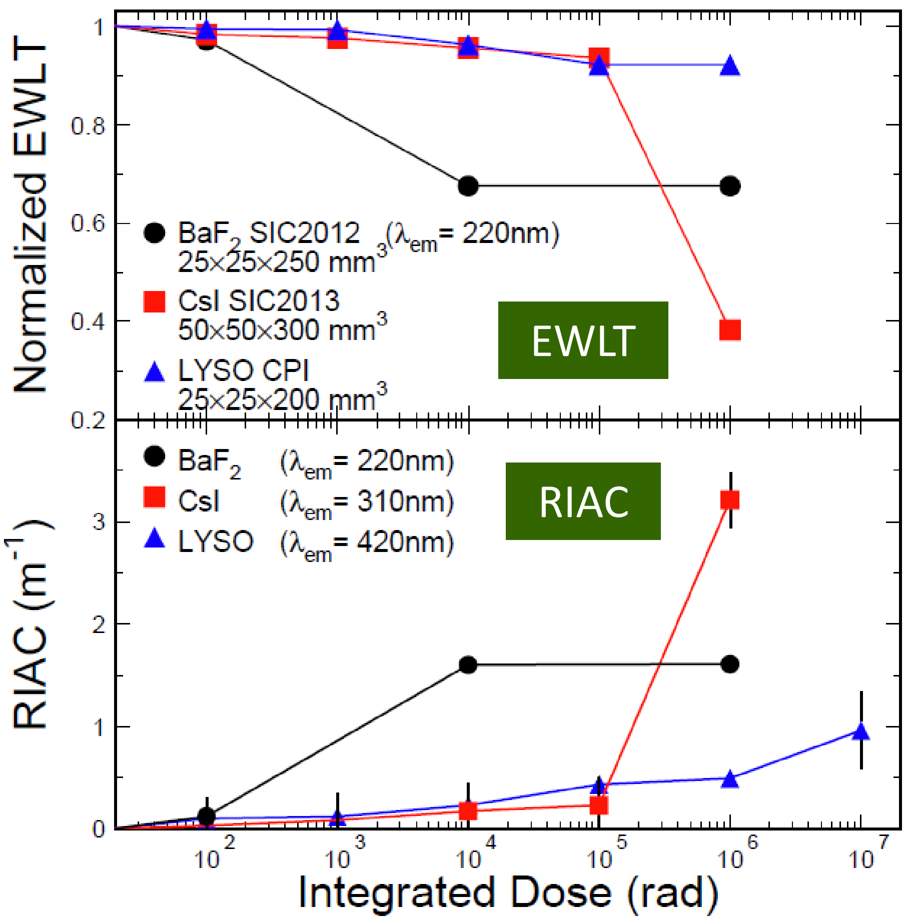


Data of Kharkov crystals: *Nucl. Ins. Meth. A* 326 (1993) 508-512

Comparison of Radiation Hardness

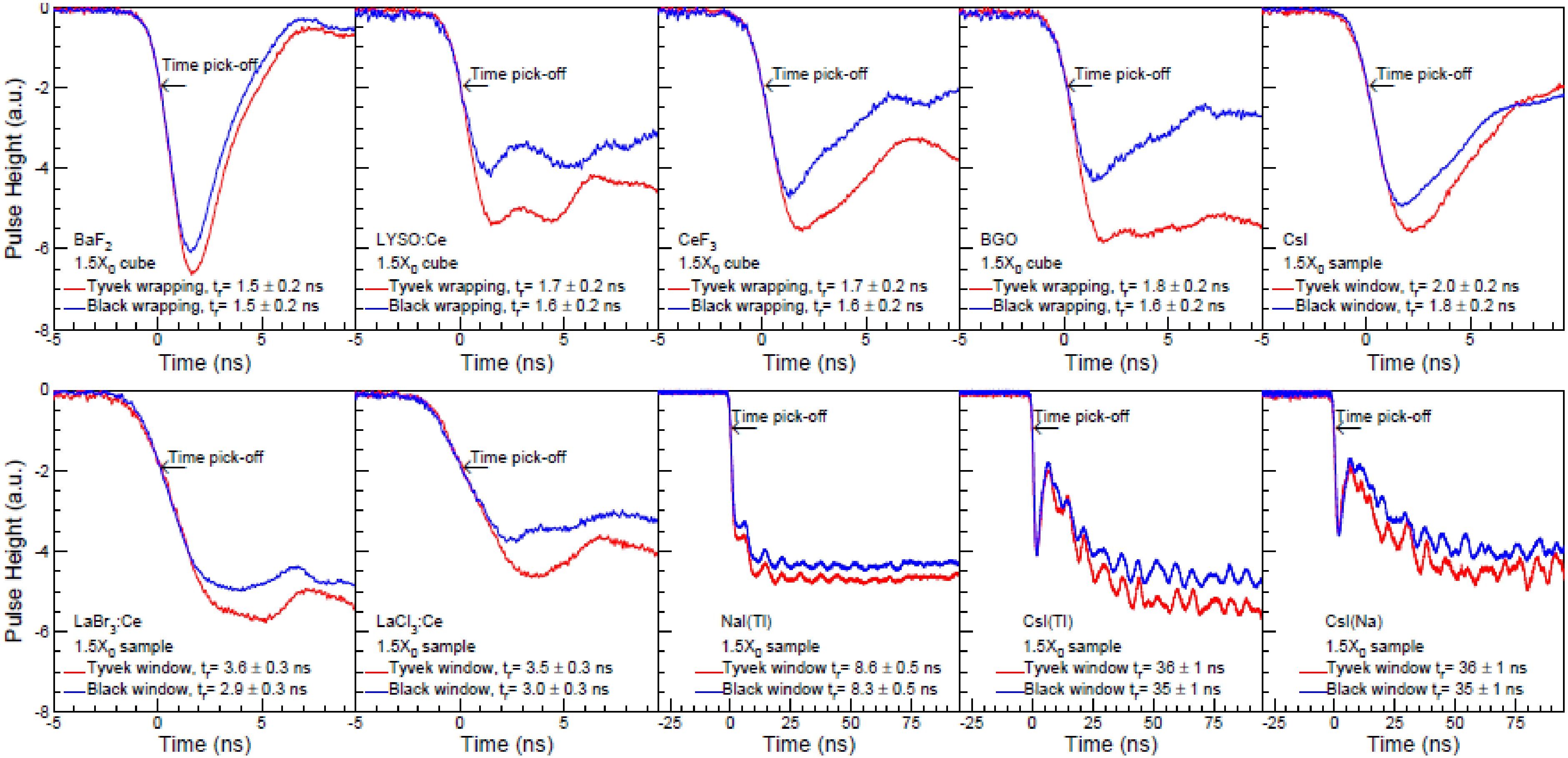
LYSO is the best in radiation hardness. BaF_2/CsI is good at high/low dose





Rising Time for 1.5 X_0 Samples

Talk in the time resolution workshop at U. Chicago, 4/28/2011: Agilent MSO9254A (2.5 GHz) DSO with 0.14 ns rise time Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns



Measured rising time is dominated by photo-detector response, and is affected by light propagation in crystal.

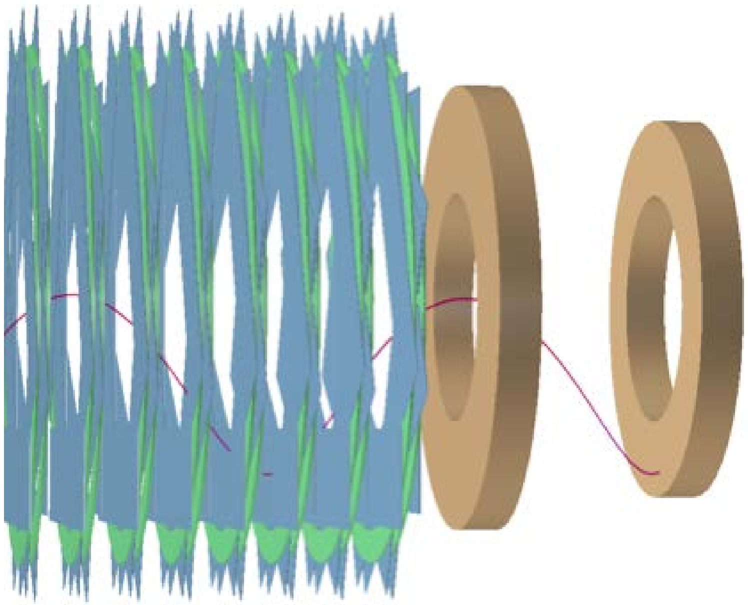
Figure of Merit for Timing

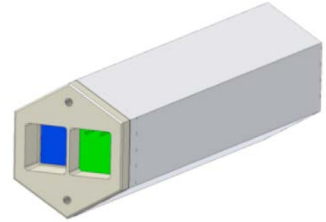
FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 X_0 crystal samples.

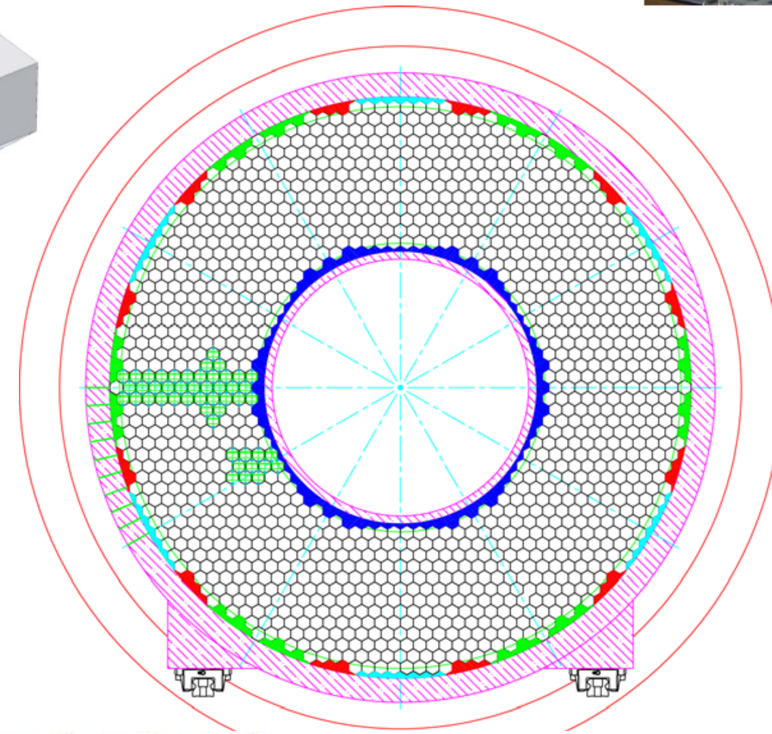
Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5

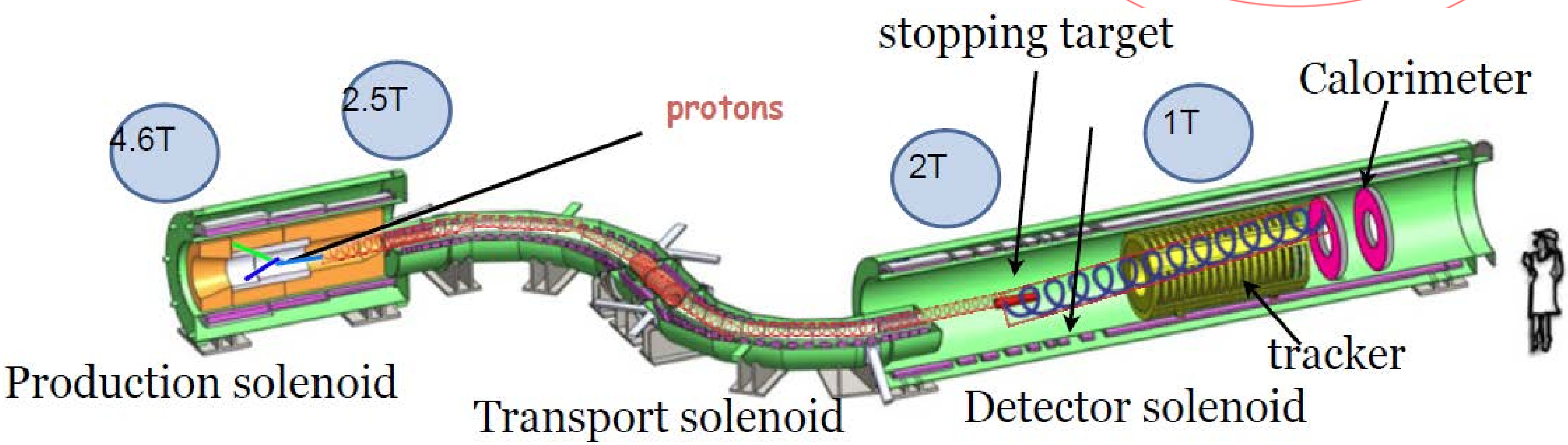
The best crystal scintillator for ultra-fast timing is BaF_2 and LSO(Ce/Ca) and LYSO(Ce). $LaBr_3$ is a material with high potential.

Mu2e BaF_2 Calorimeter





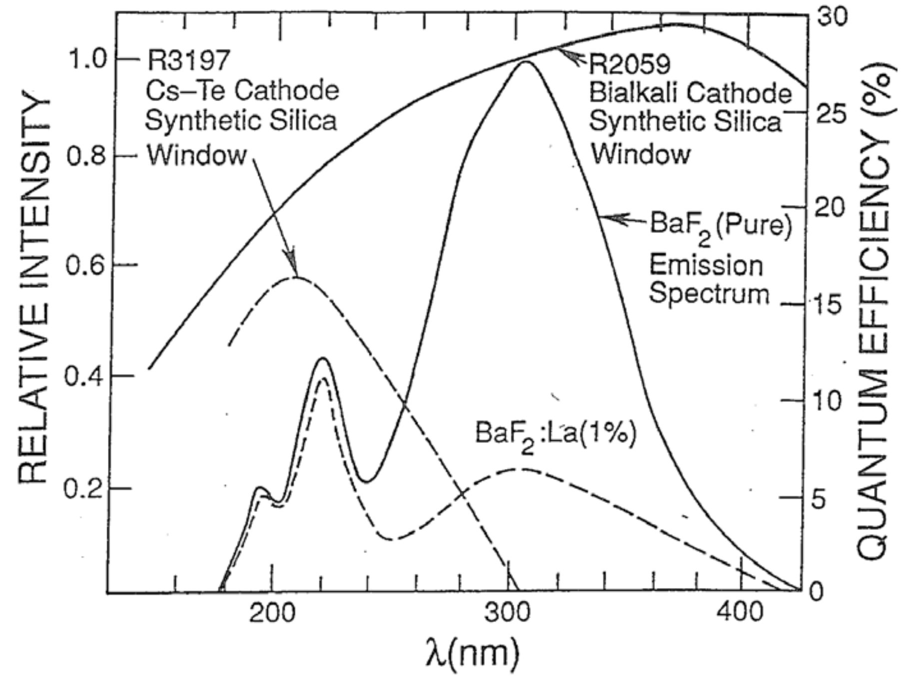


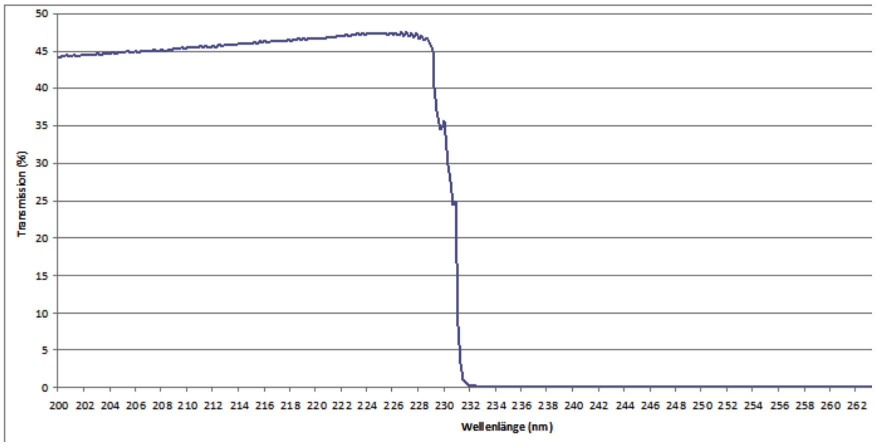


BaF_2 for Very Fast Calorimeter

The fast component of BaF_2 crystals at 220 nm has a similar light output as pure CsI and sub-ns decay time.

Spectroscopic selection of fast component may be achieved with solar blind photocathode or short pass filter.

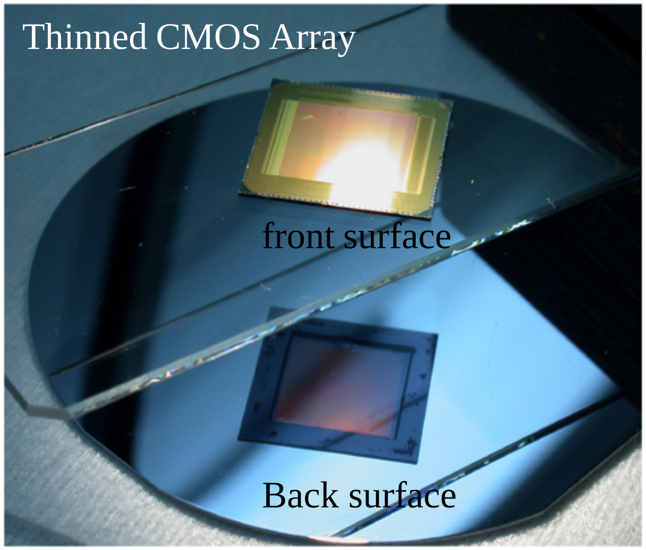


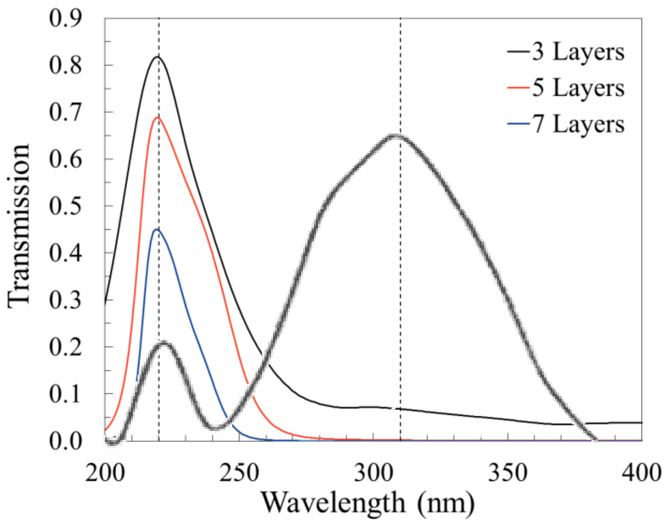


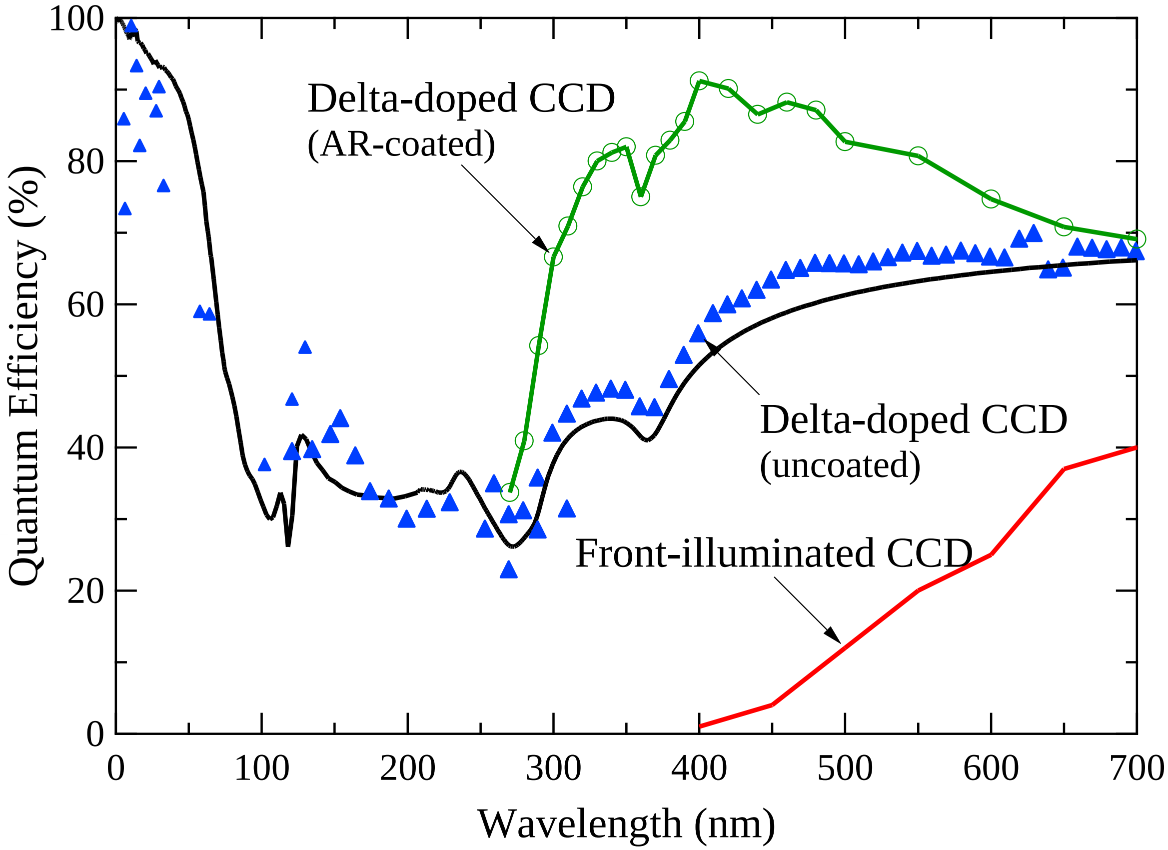
R. Novotny, private communication

Delta-doping for CCD detectors

D. Hitlin, Talk in NSTR2014, February 28, 2014, with JPL





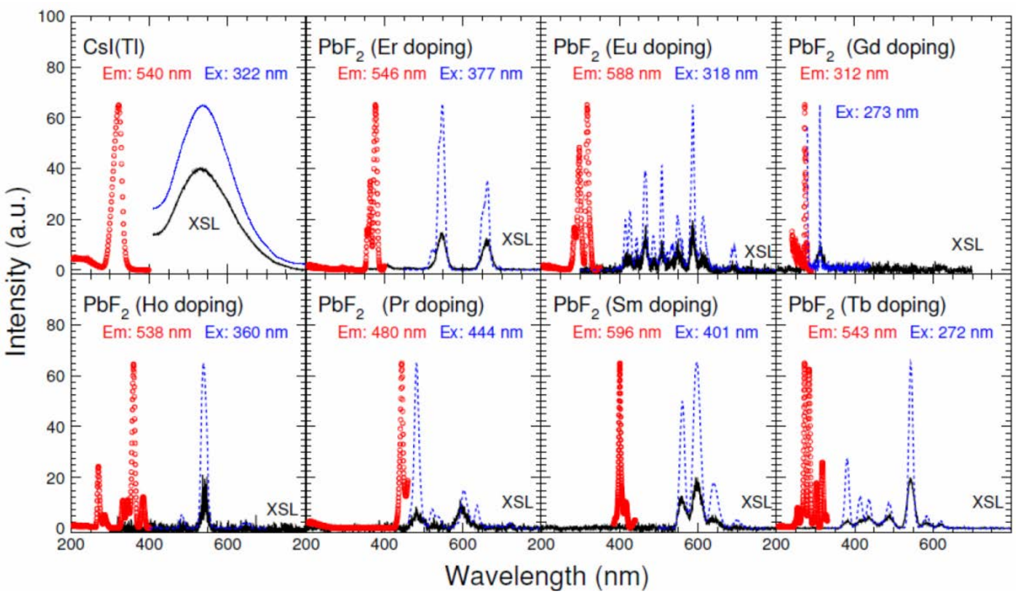


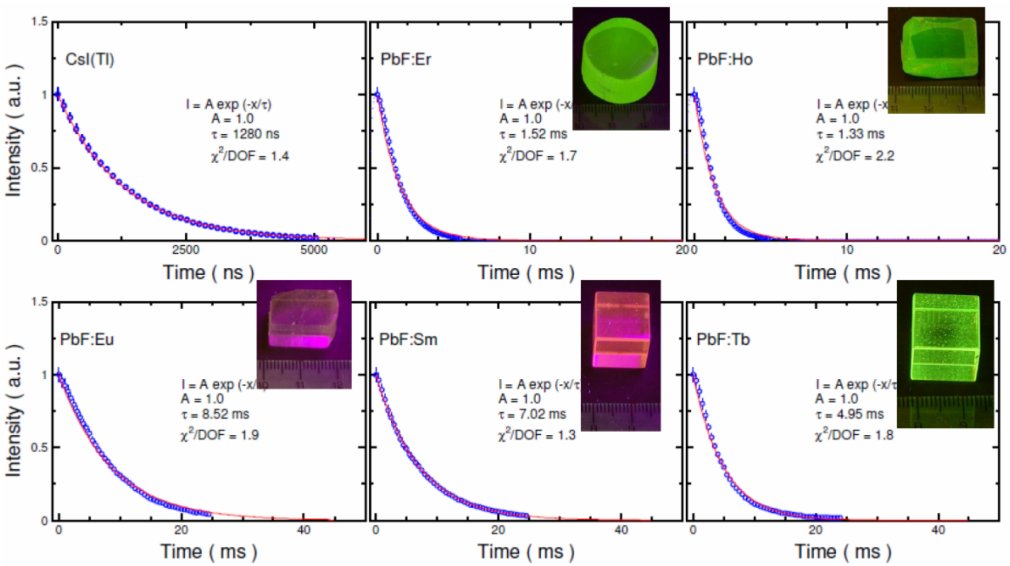
S. Nikzad, "Ultrastable and uniform EUV and UV detectors," *SPIE Proc.*, Vol. 4139, pp. 250-258 (2000).

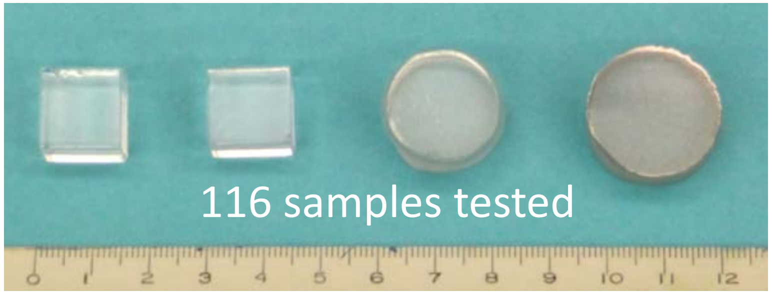
Candidate Crystals for HHCAL

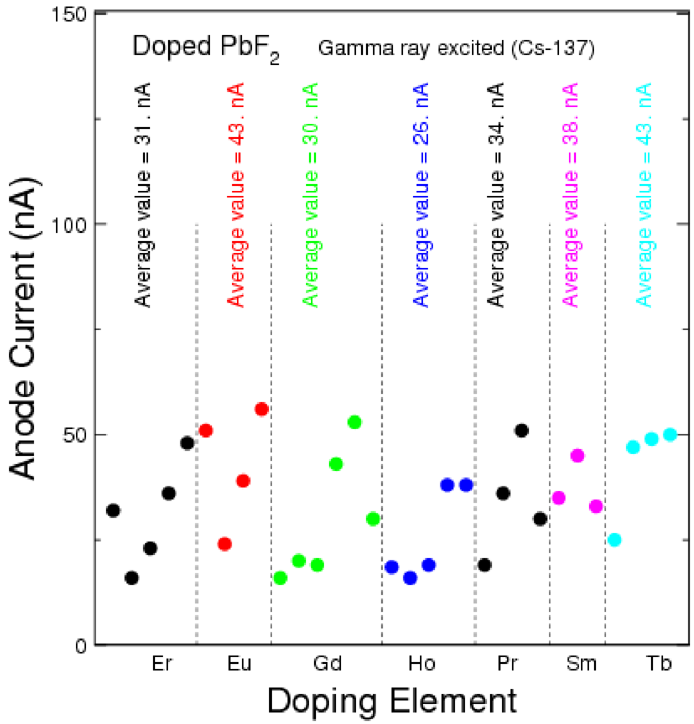
Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$PbWO_4$ (PWO)	PbF_2	PbClF	$Bi_4Si_3O_{12}$ (BSO)
ρ (g/cm^3)	7.13	**8.29**	**7.77**	7.11	6.8
λ_I (cm)	22.8	**20.7**	**21.0**	24.3	23.1
n @ λ_{max}	2.15	2.20	1.82	2.15	2.06
τ_{decay} (ns)	300	30/10	**?**	30	100
λ_{max} (nm)	480	425/420	**?**	420	470
Cut-off λ (nm)	**310**	350	**250**	**280**	**300**
Light Output (%)	100	1.4/0.37	**?**	17	20
Melting point (°C)	**1050**	**1123**	**842**	**608**	**1030**
Raw Material Cost (%)	100	49	**29**	**29**	47

Search for Scintillation in Doped PbF_2



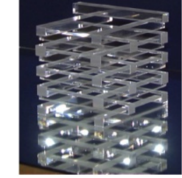


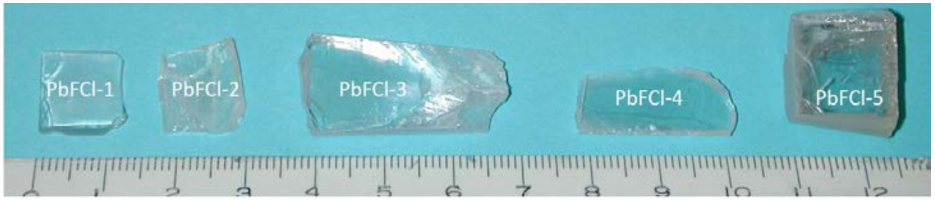


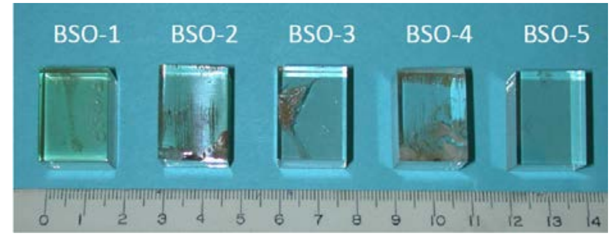


Will look performance at low temperature with the FLS920 fluorescence lifetime spectrometer

Other Materials: PbFCl & BSO

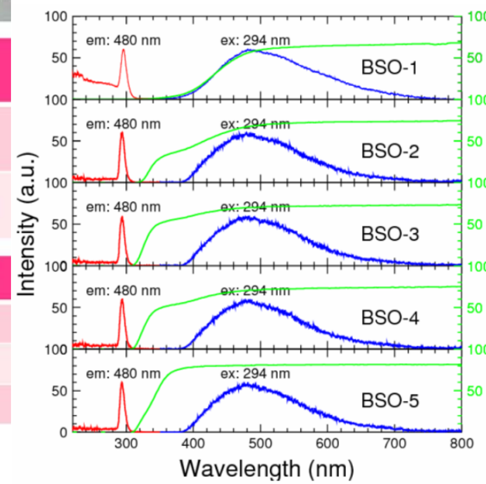


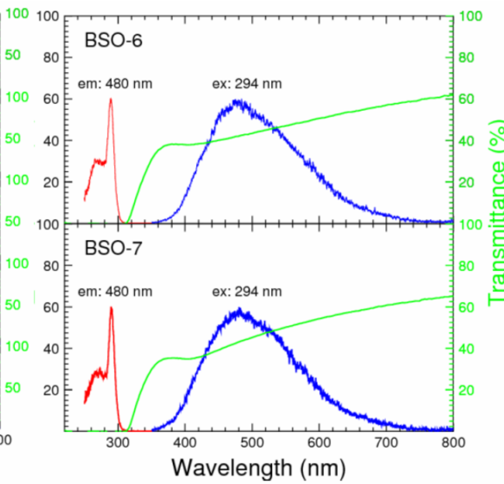


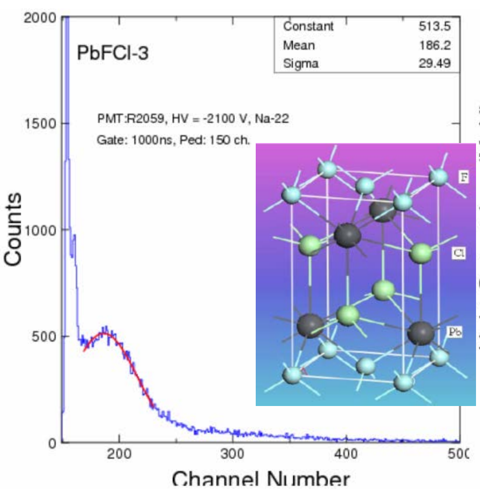


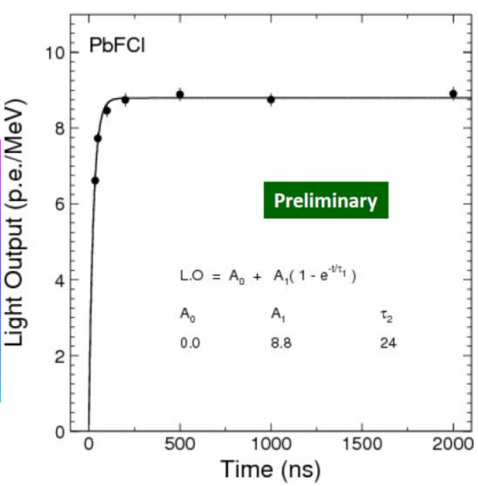
ID	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
Doping	--	Na 0.5at%	--	--	
Dimension (mm)	10x10x2	10x10x2	30x10x5	20x10x3	~10x10x9

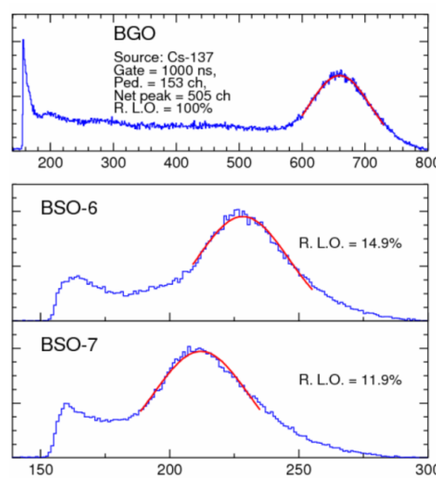
ID	PWO	PbFCl-1	PbFCl-2	PbFCl-3	PbFCl-4	PbFCl-5
X-luminescence		Peaked @ 420 nm				
L.O. (% PWO)	100	14	64	33	35	31
L.O. (% BGO)	1.8	0.25	1.1	0.59	0.63	0.56

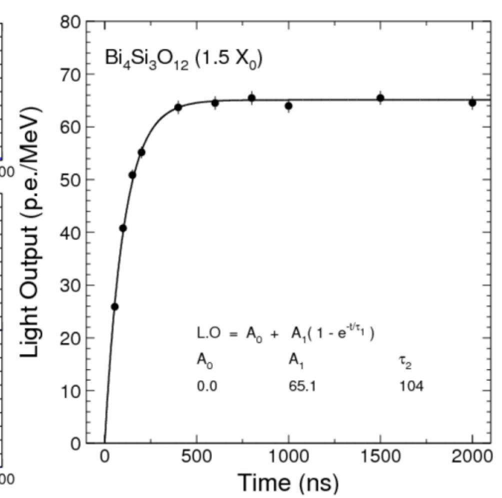




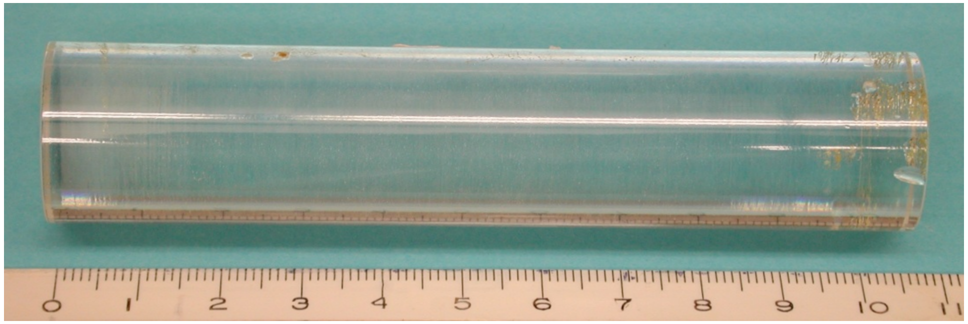




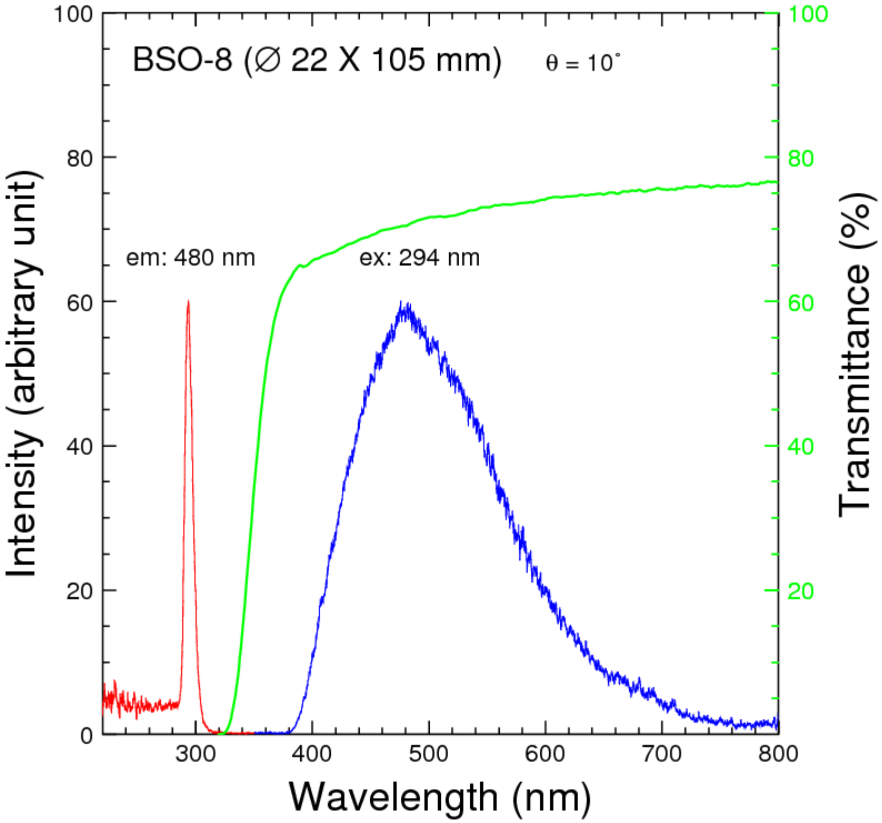


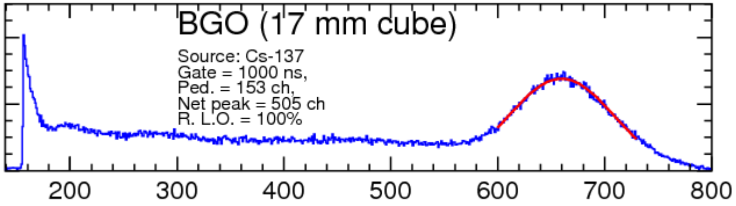


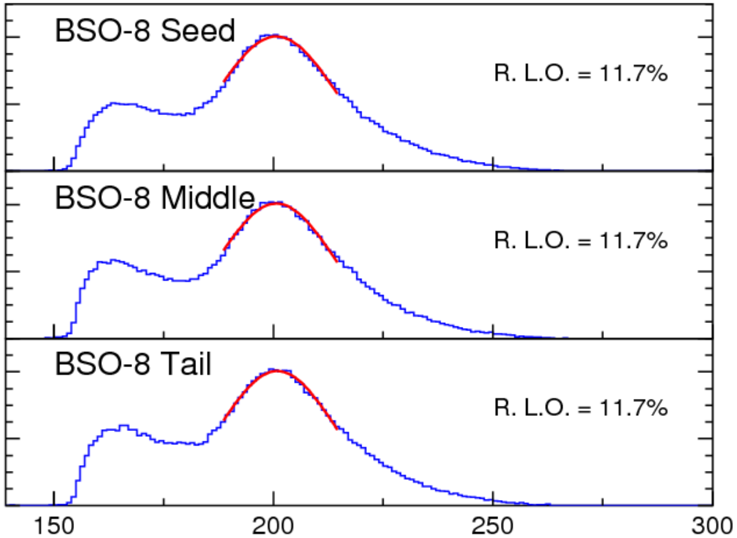
Large Size BSO Sample



A Φ22 X 105 mm BSO crystal shows good transparency and longitudinal uniformity.
See talk O4-19 for the details.







Summary

- Bright, fast and radiation hard LSO/LYSO crystals may be used for a total absorption ECAL. LYSO/W Shashlik calorimeter is one of two options for CMS FCAL upgrade technical report for HL-LHC.
- Crystal calorimeters with more than ten times faster rate/timing capability require using very fast crystals, e.g. sub-ns decay time of the BaF_2 fast scintillation component.
- Crystals (PbF_2, PbFCl & BSO) may provide a foundation for a homogeneous hadron calorimeter with dual readout for both Cherenkov and scintillation light to achieve good jet mass resolution for ILC/CLIC.
- Novel materials, such as crystals, ceramics and glasses, may play important role in future HEP experiments.